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DIVISION OF FISHERIES
INVESTIGATIONAL REPORT No. 14

THE PERIODIC MORTALITY OF FISH IN THE WALVIS REGION

A PHENOMENON WITHIN THE BENGUELA CURRENT

(With a Summary in Afrikaans and German)

BY

W. J. COPENHAGEN, O.B.E., M.Sc., F.R.I.C., F.R.S.S.A.
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THE BENGUELA CURRENT

SECTION I.

(*a*) General Description.

Before the phenomenon of the periodic mass mortality of fish in the Walvis region is dealt with, it is necessary that the conditions in the Benguela current should first be appreciated.

The name Benguela current or South African West Coast current is used to denote that part of the South Atlantic anticyclonic circulation in which a northerly current is conspicuous, and whose physical, chemical and biological characteristics are most affected by admixture with water from the lower layers. This current represents a narrow belt of cold water which runs up the west coast from Cape Point to the vicinity of the Kunene River, the latter being the boundary between South West Africa and Angola. The waters are generally coldest inshore, and exhibit an increasing temperature with distance offshore.

Upwelling from a layer of Antarctic intermediate water, this current is high in nutrient salts, well seeded with phytoplankton and hence a wealth of marine life, giving rise in the south to rich trawling areas. Surface fish also abound in this current, and rock lobster beds extend from the Cape to north of Luderitzbücht. The total value of fish and other marine products taken from the Benguela current in 1951 exceeded £7,000,000.

Deacon (1937) showed that the cold water upwelling in the Benguela was derived from the Antarctic intermediate current. This current originates about 100–200 miles from the Antarctic convergence situated about 50°S. It is formed by the sudden sinking of the Antarctic surface water. This surface water descends to a lower level over the slope formed by the ascent of deep warm water flowing southwards, and the Antarctic intermediate flowing northwards. The Benguela current thus exhibits marked antarctic characteristics.

Defant's (1936) description of the Benguela based on records from the " Meteor " expedition, is probably the most lucid. In agreement with the dynamics of ocean currents in the southern hemisphere, dense water of low temperature is found on the right side of the current, i.e. close to the African coast. The prevailing southerly and south-westerly winds speed the current on its northerly course. These offshore winds (particularly south-east winds in the Cape region) cause upwelling which is probably augmented by shelving bottom contours. It is interesting to note that Defant contends that, at the latitude of Swakopmund, maximum upwelling occurs in May and June, and minimum in December and January. The percentage frequency of east wind (offshore wind) in this locality bears a high correlation with this statement. In the process of upwelling, an overturning of the upper layers of the water takes place.

This is a system of shallow currents, as the entire circulation takes place above the Antarctic intermediate layer of water, and is probably confined to about 300 metres. It first becomes noticeable in the vicinity of Cape Point and starts as a narrow band of water about 20 miles in width gradually increasing in breadth. At Saldanha Bay it is about 50–60 miles broad, and at the Orange River it is about 100 miles. The total length of the Benguela is about 1,200 miles along the coast of South West Africa, and its departure from the west coast takes place at about 16° South, when the current swings in a north-westerly direction, crosses the Atlantic Ocean and merges with the Brazil inshore current flowing southwards. There is no sharp boundary between the Benguela current and the South Atlantic Ocean, the one merging gradually into the other.

A general description of the Benguela current and its relation to the adjoining water masses is given in a recent publication by Clowes (1950).

(*b*) Current Data and Speed of Upwelling.

Current Data.

The strength of the Benguela current given in Admiralty current charts (1947) is 10–25 miles per day, and the general set is parallel to the coast. According to Admiralty publications, the set may sometimes be in a southerly direction—generally after rains and northerly winds. These abnormal conditions continue for two or three days and seldom are of a week's duration. During calms, especially, the currents are very irregular. Ships have reported that during fogs a southward set has been observed, and it has also been noted that this has been associated with unusually high surface sea temperatures.

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Speed of Upwelling.

Walter (1937) has shown a correlation between the strength of the south-west wind at Luderitzbücht, and the drop in the temperature of the sea water inshore. Wind velocities between 5 and 10 metres per second bring about decreases in surface temperature from 3–4°C.

(*c*) Meteorological Data.

During the summer months an anticyclonic area lies off the west coast of South Africa with its axis along about Lat. 30° South. This anticyclonic area is of large extent and sometimes has a secondary area of high pressure lying southward of Cape Agulhas. The pressure gradients are steep on the southern side, and moderate on the northern side of these areas.

The well-known " South Easter " during the summer is probably caused by a combination of these two high pressure systems. The wind blows from the south-east in the vicinity of False Bay and the Cape Peninsula parallel to the northerly isobars of the secondary high, and then merges into the southerly winds of the eastern side of the main area of high pressure. During the summer months these winds are common, and at times blow with gale force. These winds extend along the coast from Cape Point to about the Kunene River (Lat. 16°S.). Northward of this, the winds appear to merge into the ordinary South East Trade winds.

During the winter months the system is more complex, the area of high pressure lies much farther north, and the secondary high pressure systems do not usually appear. At the Cape, the prevailing weather is governed by a series of depressions, passing to the eastward with their centres south of the Cape. With the passing of these depressions, gales commencing from the north-west and backing to south-westerly, are of frequent occurrence. The effect of these depressions extends a considerable distance northwards, but as the distance to the north and northwest from the track of these storm centres increases, the winds are usually felt only from a south-west to southerly direction. Generally speaking, the winds from a southerly direction are the most usual along the whole coast, and northward of the Orange River strong winds other than SW–S are seldom experienced, except for occasional east winds (Berg winds).

It will thus be seen that the general tendency of the prevailing winds is to speed the Benguela current northwards along the coast, until about Lat. 16° South when the winds merge into the S.E. Trade Wind—this current is then deflected into the South-East Trade Drift, across the Atlantic.

At certain times, however, northerly to westerly winds are experienced, particularly in the Walvis region. These exert a profound influence on the directional flow of the water. A reversal, i.e. a flow in a southward direction, was discernable on one occasion as far south as the Orange River [Walter (1937)].

The cold upwelling water close to the coast has a marked influence on the climate of the coastal belt, and may be a cause of the almost complete absence of rain. The air at times has a high degree of relative humidity, but with northerly wind this invariably results in dense fog banks, particularly in the Walvis region. Extending from the Orange River up to the Kunene River is an arid coastal belt about a hundred miles in width with practically no vegetation, which is known as the Namib Desert. To the north of Swakopmund there are numerous salt deposits, and on the beaches in this region are rocky outcrops. Southwards of Walvis up to about the 26th parallel the beaches are for the most part sandy. These arid conditions also pertain to numerous small islands off the coast and make the accumulation of valuable guano deposits possible.

(*d*) Coastal Upwelling and Bottom Contours.

The first indication of upwelling on the west coast is the extremely low temperature experienced inshore. In order to compare upwelling, a suitable diagram was made, in which all recorded surface temperatures were plotted. Bottom contours were drawn, showing the 50, 100, 150, 200, 500 and 1,000-metre depths. Soundings were taken from Admiralty charts as well as from charts made by the oceanographical ships " Pickle ", " Africana ", " Discovery " and " Meteor ".

For nearly all the year, an area extending from Cape Point (latitude 35°) to about 18° South latitude, and about 60 miles offshore, exhibits a surface sea temperature of 15·5° C., with lower temperatures closer inshore (at some places 9–10° C.). 15·5° C. is usually found 60 miles seaward and the surface temperatures gradually rise, attaining 18° C. about 100 miles offshore.

Northwards of 18° South, temperatures of 18° C. and higher are observed as close inshore as 20 miles off the coast. At the latitude of Saldanha Bay (33° South), the isotherm of 15·5 bends sharply inshore towards the Cape Peninsula, where it is about 25 miles offshore, finally converging to the shore at Cape Point. To the south-east of Cape Point, the influence of the warm Agulhas current is apparent.

From time to time anomalies appear in the normal surface temperature distribution. Most of these have been associated with northerly and westerly winds. During such occasions warmer water has invaded the Benguela current, and temperatures inshore at Swakopmund and Walvis have sometimes risen to 24° C.

The intensity of upwelling is estimated by noting the reduction of surface temperature inshore compared with an arbitrary standard. McEwen (1912), in his investigations of upwelling off the Californian coast, selects as his standard the surface temperature of a point in mid-ocean, having the same latitude. Thus, the difference between the observed temperature off the coast, and the mid-ocean temperature, is assumed to be due entirely to the admixture of cold water upwelling from the adjacent ocean bottom with the surface water. Schott (1931) uses as his standard of comparison the mean surface temperature at a distance of 100 miles offshore. This has the advantage that both temperatures will be subject to the same local major variations. Taking both these normal thermals into consideration, and the fact that comparatively large variations of temperatures have been observed at times even 150 miles offshore, a normal thermal has been selected at a distance of 200 miles offshore at the same latitude, due regard being made for seasons. The so-called divergence lines of Defant are likewise of this order of distance offshore. Inside these divergence lines, isotherms and isohalines bend towards the surface. Outside the divergence line, the isotherms and isohalines are nearly horizontal.

Before the temperature differences between inshore temperatures and our thermal normal (200 miles offshore) are examined, reference to the surface temperature contour diagram will reveal a high correlation between the location of areas of cold water and the submerged valleys, where the depth increases rapidly with distance offshore. For example, the cold areas north of Cape Point and Saldanha Bay are close to two submerged valleys in the 200-metre bottom contour.

The main cold localities and submerged valleys are as follows:—

(1) Cape Point locality 200-metre contour about 10 miles offshore.
(2) Saldanha Bay locality 200-metre contour about 12 miles offshore.
(3) Luderitzbücht locality 200-metre contour about 20 miles offshore.
(4) Kunene River locality 200-metre contour about 18 miles offshore.
(5) Great Fish Bay locality 200-metre contour about 10 miles offshore.

Subsidiary cold localities and submerged valleys:—

(6) Hondeklip Bay locality 150-metre contour about 15 miles offshore.
(7) Walvis Bay locality 100-metre contour about 10 miles offshore.

At localities (4) and (5) above, only isolated surface temperatures have been recorded, and are not included in the list of regions of upwelling.

TABLE I.

	Cape Point.	Saldanha Bay.	Luderitz.	Hondeklip Bay.	Walvis Bay.
Surface temperature: 200 miles off coast—					
(FEB.)	20° C.	20° C.	20° C.	20° C.	20° C.
Thermal normal—					
(MAY)	17	17	18	17	19
(AUG.)	15	15	16	15	16
(NOV.)	16	16	17	17	18
Mean (average) surface temperatures—					
(FEB.)	9	13	12	—	15
(MAY)	12	11	—	—	16
(AUG.)	12	11	11	10	14
(NOV.)	9	14	10	14	15
Differences between—					
Thermal—					
(FEB.)	−11	−7	−8	—	−5
(MAY)	−5	−6	—	—	−3
Normal, and surface, 0–5—					
(AUG.)	−3	−4	−5	−5	−2
(NOV.)	−7	−2	−7	−3	−3
Mean difference of annual observations	−6° C.	−5° C.	−6° C.	−4° C.	−4° C.

From the above table, it appears that the active centres of upwelling are: Cape Point, Saldanha Bay and Luderitzbücht. Subsidiary centres are at Hondeklip Bay and Walvis Bay. Upwelling, although an active process operating throughout the year, is an intermittent process.

The bottom contour diagram (Plate I), reveals that between Cape Point and Great Fish Bay the Benguela current moves over an elevated plateau. The northern end of the plateau connects up with the submerged Walvis ridge—the latter being a branch of the Atlantic ridge. From the submarine valley at Luderitzbücht, the 50–200-metre contours broaden to a maximum, the 200-metre contour being almost 60 miles offshore. This broadening gives rise to a large euphotic zone in this locality. The effect of the Walvis ridge (see Plate IX) which connects obliquely with the African continent, separates the deep water masses (3,000 to 5,000 metres) to the north and south of the ridge. Closer inshore, the bottom water of the Benguela current is probably also impeded.

(*e*) Bottom Deposits.

There are certain areas, especially the trawling grounds, that are characterized by long stretches of green mud. West of Cape Point and about 10–20 miles offshore is an area of green mud and dark fine sand. The inner boundary closely follows the 100-fathoms (183 metres) line, and the average width is about 30 miles. This line extends up to Saldanha Bay, and has hitherto proved to be a prolific fishing ground for Stockfish (*Merluccius capensis*) and Kingklip (*Genypterus capensis*).

Between Saldanha Bay and Cape Columbine (latitude 33° South) rough ground unsuitable for trawling is encountered. To the west of Cape Columbine smooth bottom commences again, and the stretch of green mud now forks into two distinct lanes, which continue almost uninterruptedly as far as the Orange River.

The inner lane is a narrow band three to four miles in width, and is about a mile and a half offshore, and consists of a soft, fine, almost slimy mud, and contains numerous tubicolous polychaete worms. Certain areas of this soft mud, particularly in the proximity of Lamberts Bay, contain small quantities of sulphuretted hydrogen. In this inshore band considerable quantities of the West Coast Sole (*Austroglossus microlepis*) are caught.

The outer area of soft bottom consists again of green mud and dark fine sand, and the width here is of the order of about 60 miles. Northward of the latitude of the Orange River, it narrows abruptly and foul ground is again encountered. The outer lane also affords excellent trawling ground for Stockfish and Kingklip. Between the Orange River and Luderitzbücht very few fishery surveys have been carried out.

The extent of the dark green sulphide mud of the azoic area in the Walvis region lying to the north of Luderitzbücht is described on page 10 of this paper.

Mention must be made of two peculiar deposits, i.e. phosphatic nodules, and considerable quantities of bones of whales.

Cayeux (1934) in his study of phosphate nodules of the Agulhas Bank describes two specimens obtained from a position due west of Cape Town from 229 metres depth. These contained over 18 per cent. of phosphate. At latitude 33° 28·5′ South, longitude 17° 29′ East (westward of Dassen Island) at a depth of 512 metres numerous skeletal bones of whales and manganese nodules were found.

SECTION II.

(*a*) The Chemical and Physical Characteristics of the Current.

For the greater part of the year, especially during the periods of southerly winds, it would seem that the chemical and physical characteristics are subject to only slight variations. A typical example of the southern portion of the Benguela current (27 miles offshore, vicinity of St. Helena Bay), is shown below. It is taken from Discovery Reports (1929–1931).

Discovery Station No. 408:—
Date: 20/7/1930.
Time: 0720.
Wind: S.S.W. 12 knots.
Position: Lat. 33° 04′ South.
Long. 17° 26′ East.
Sounding: 412 metres, bottom hard.

The oxygen figures are in cubic centimetres/litre. The phosphate in milligram-atoms phosphorus/cubic metre.

TABLE II.

Depth.	Temp. °C.	S. ‰.	σt.	pH.	P.	O_2.
0	13·53	35·03	26·31	8·32	0·35	5·44
100	10·29	34·88	26·82	8·10	0·83	4·21
400	5·77	34·43	27·15	7·95	—	4·35

(*b*) Effects of Northerly and Westerly Winds.

During continued spells of northerly and westerly winds, however, violent fluctuations are likely to occur. This is due to Atlantic Ocean water entering the region of the Benguela current, and the tendency to suppress upwelling. The figures in Table III below are typical and are from surface water two and a half miles offshore, three miles south of Cape Town.

TABLE III.

Date.	Temp. °C.	Wind (Beaufort Scale).	Salinity ‰.	P.
August 17, 1949...	15·0	N.N.W. 5	35·26	0·473
September 3, 1949.	14·1	N. 4	35·17	0·589
September 22, 1949.	12·0	S.E. 6	35·01	0·964
October 11, 1949..	10·3	S.E. 4	35·05	1·181
November 17, 1949.	9·7	S.E. 3	34·72	1·632

The influences of oceanic water are three-fold:—

(1) Raises the temperature.

(2) Increases the salinity.

(3) Decreases the phosphate.

The heating effect of oceanic water in the Walvis region (brought in by northerly and westerly winds) is stated on page 13 of this paper, and on occasions the inshore surface temperatures have been elevated to 24° C.

The phosphate content of the surface water is normally relatively high, i.e. between 0·2–2·0 (milligram-atoms of phosphorus per cubic metre). Hentschel and Wattenberg (1930) consider that the Benguela current is one of the richest areas in the world in this respect.

(*c*) Influence of the Orange River.

It has been estimated that the Orange River carries annually into the sea about 7,000 million tons of water containing some 50 million tons of soil, mostly in the form of clay, silt and fine sand (see Plate I — bottom contours, probable effect of the suspension on bottom contours between latitudes 28°–30° South). It is probable that the organic matter in this suspension has a profound influence on the dissolved oxygen in the lower layers of water in the Benguela current in this locality. Data obtained from "William Scoresby's" results in March, 1950, at latitude 28° 40′ (Orange River), were as follows:—

Depth.	Distance from River Mouth (Miles).	Oxygen Millilitres/litre.
69 metres.....	15	1·67 at 50 metres depth.
121 metres.....	50	0·87 at 100 metres depth.
188 metres.....	55	2·27 at 150 metres depth.

The effect of the organic matter in suspension on dissolved oxygen is possibly localized. Besides organic matter, nutrient salts, phosphate, potash, etc., are also contributed to the Benguela current by the slow solution of this suspended matter.

The specific conditions relating to the Walvis region are described on page 12 of this paper.

SECTION III.

(*a*) Plankton in the Current.

Several expeditions have made most comprehensive plankton observations in the Atlantic. Their studies included several stations in the Benguela current. Their work here was part of an oceanic survey planned on a far wider scale than could be desired for a detailed study of the Benguela current itself. The German Atlantic expedition ship "Meteor" and the "Discovery" figure prominently in this respect. Recently the R.R.S. "William Scoresby" made two surveys aimed directly at a more detailed study of the current. Some of their results have kindly been made available by permission of the Director of the National Institute of Oceanography. The Union Government's fisheries research ship "Africana II" is at present engaged on an extensive pilchard (*Sardinops ocellata*) survey. This commenced in April, 1950, and operations are mainly in the 100-miles wide sea-area between Table Bay and the Orange River.

Hentschel and Wattenberg (1930) showed that the greatest concentrations of plankton found in the Atlantic were in the portion of the Benguela current lying between 17° and 25° South latitude. Quantitative figures reflecting the seasonal variation of phytoplankton of Table Bay are given by the writer and Mrs. W. J. Copenhagen (1949).

The diatoms found between Lamberts Bay and Cape Town have been described by Boden (1950). In March, 1950, the scientific staff of the R.R.S. "William Scoresby" observed enormous long lanes of an olive-green colour on the surface of the sea some 20 miles from the land off Walvis Bay.

A microscopic examination revealed countless masses of diatoms of the *Chaetoceras* species. Although a search was made for the dinoflagellate *Gymnodinium*, none was observed. However, an allied species, viz. *Glenodinium*, was found in considerable quantities by the Danish expedition ship " Galathea " in the vicinity of Walvis Bay in December, 1950.

During May, 1950, 18 samples of phytoplankton were obtained from Walvis Bay and vicinity (see Appendix II). Although procured in late autumn (southern hemisphere), two of the samples were extremely dense and gelatinous, and were comparable with those obtained at the Cape at the spring outburst. A list of the dominant species found in these samples will be found in Appendix II. In the same month two samples of phytoplankton were obtained from St. Helena Bay. Both these were typical of the Cape winter tow-net catches, i.e. sparse, and the dominant species similar to those found on a former occasion. [W. J. and L. D. Copenhagen (1949).]

SECTIONS IV – VII.

THE PERIODIC MORTALITY OF FISH IN THE WALVIS REGION.

SECTION IV.

(*a*) Region involved and Time of the Year.

For many years dead and dying fish, as well as cephalopods, lamellibranchs and other forms of marine life, have been observed in the sea and on the beaches of Spencer Bay, Conception Bay, Walvis Bay, Swakopmund and even as far north as the Ogab River, i.e. between latitudes 25° South and 21° South. At times the beaches are strewn with thousands of tons of dead fish, whilst on other occasions only comparatively small numbers of dead fish are observed (see Plate III, Figs. 1 and 2).

One of the earliest descriptions of a mass mortality is given by Morrell (1828), who states:—

> " September 20th, 1828. At Elizabeth Bay, Possession Island, South West Africa.
>
> On the surface of the island I saw the effects of a pestilence or plague which had visited the amphibious inhabitants of the ocean with as much malignancy as Asiatic cholera has on bipeds on the land. The whole island was literally covered with the carcasses of fur seal (*Arctocephalus pusillens*) with skins still on them. I should say there were about half a million of them, and they had been dead for five years."

Whether the seals died from disease or lack of food is not known. The latter possibility should not be excluded. An extremely comprehensive list of the occasions when dead fish were observed at sea, or washed up on the beaches in the Walvis region is given by Brongersma-Sanders (1948), who sets out chronologically the records during the period 1837 to 1943. The 1944 and subsequent records were obtained by the writer during a recent visit.

TABLE IV.

Year.	Observer.	Month.
1837.....	Alexander.....	—
1849 (?).	Chapman.....	—
1851.....	Andersson.....	December.
1860.....	Chapman.....	December.
1880.....	Gilchrist and others	—
1881.....	Pechuel Loesche..	December.
1882.....	Arbthudt.....	January...
1883.....	Stappf.....	December.
1884.....	Stappf.....	December.
1920.....	Reuning.....	December.
1924.....	Reuning.....	December.
1925.....	Von Bonde.....	December.
1927.....	Classen.....	January.
1928.....	Marchand.....	February.
1929.....	Schakenbeck.....	December.
1933/34..	Offen.....	December and January.
1938.....	Brongersma-Sanders.....	November.
1943.....	McConnel.....	January.
1944.....	H. Offen.....	December.
1947.....	H. Offen.....	December.
1948.....	H. Offen.....	January, February, December.
1949.....	H. Offen.....	January.
1950.....	H. Offen.....	January and February–also March, 8th–13th.
1951.....	W. J. Copenhagen	December, 1950, February and March.

The records in the early years are from chance travellers and are based mainly on evidence within Walvis Bay itself, or the adjoining beaches.

Moreover, it is quite obvious that if the current should carry dead fish out to sea or deposit them on a stretch of uninhabited coast, there would be no tangible evidence of a mortality.

Classen (1930) considers that some mortality occurs every year, and it may even be four or five times a season. The writer is also of this opinion. It is significant, however, that these mortalities, and in many instances, mass mortalities, invariably occur during the months of December and January. On rare occasions dead fish have been noted during other months than December and January.

A scrutiny of the meteorological records (*ex* Africa Pilot) of four ports, i.e. Cape Town, Port Nolloth, Walvis Bay and Mossamedes, reveals that:—

(*a*) Northerly winds are at a maximum at Walvis Bay during December and January;

(*b*) southerly winds are at a minimum during December and January at Walvis Bay;

(*c*) Cape Town, Port Nolloth and Mossamedes have their maximum occurrence of northerly winds during the southern hemisphere winter months, i.e. June, July and August, and maximum of southerly winds during the summer.

It is suggested, therefore, that a correlation exists between the occurrence of mass mortalities and the incidence of northerly winds in the Walvis region.

(*b*) Island Phenomena and Sulphuretted Hydrogen Gas.

The most remarkable phenomena in this region are the sudden appearance and disappearance of mud islands. The first recorded mud island appeared inside Walvis Bay and was described by Waldron (1901) (see Plate IV).

Pelican Point, the western boundary of Walvis Bay, is a low sandy spit, and a lighthouse has been erected there. At a distance of about one cable (600 feet) eastward of the lighthouse and inside the bay, there is a depth of eight fathoms (14 metres). On the 1st June, 1900, a mud island suddenly appeared from the depths of the bay at this point. The island was approximately 150 feet long and 30 feet wide, and a height about 15 feet above the surface of the sea. A very strong odour of sulphuretted hydrogen prevailed and this smell was noticed at Swakopmund some 25 miles distant. Steam appeared to issue from the northern side of the island. The water around the island was very dirty, and the surface was covered with bubbles. Some dead fish had been washed up. An officer from the Cape Garrison Artillery swam off to the island from a boat. Although steam was still issuing, the water was very cold and no heat was felt on the island. A sample of the mud was procured. On the 4th of June, a second visit was made and the size of the island was found to have diminished owing to lumps of mud falling into the sea. On the 7th of June, the entire island disappeared and soundings of the sea bottom indicated that the original depth of eight fathoms was restored. It is interesting to note that a submarine cable was neatly fractured a few weeks earlier, six miles to the north of where the island appeared. Station No. 6 in Plate VI is the approximate position at which the island made its appearance.

On 6th March, 1951, three small islands appeared above the sea to the westward of Pelican Point. The first island appeared about 6.40 p.m. and rose from a bubbling sea. It remained about an hour and then subsided beneath the waves. It was about 300 feet in length, brown in colour and about 100 yards offshore. The other two islands were further out to seaward and appeared about the same time. They remained until daylight faded, and by morning had disappeared.

In January, 1949, in Walvis harbour, numerous bubbles were observed coming up to the surface followed by clods of mud in many instances about a foot in diameter. These disintegrated and a smell of sulphuretted hydrogen gas was noted.

On another occasion, while a large ocean tanker was berthing and the bottom mud near to the wharf was stirred up, hundreds of soles suddenly came to the surface. A smell of sulphuretted hydrogen gas was noticeable. Many people collected baskets of soles which were eaten without any ill effects.

From the above accounts it is clear that the occurrence of mass mortalities and mud islands are associated with the odour of sulphuretted hydrogen. The concentration of this gas at times is such that pale-coloured lead paints and brass fittings on ships become blackened.

The exterior and interior of many buildings ashore also display evidence of this discoloration. Throughout the year the odour of sulphuretted hydrogen gas is evident in the atmosphere of the Walvis Bay township during the berthing of ships when onshore winds are blowing. This gas is also conspiciuous most of the year in the vicinity of the lighthouse at Pelican Point.

(*c*) Sea-bottom and Marine Life.

A remarkable feature of this region is that the sea bottom over a considerable area consists of dark green, foul-smelling mud, from which sulphuretted hydrogen is evolved.

In a previous publication by the writer (1934), it was reported that 100 gms. of mud from the anchorage at Walvis Bay contained 79 millilitres of sulphuretted hydrogen.

In 1926–1927 a preliminary survey of this region, directed by the late Dr. J. D. F. Gilchrist, was carried out by Captain Roberts and the writer, in the Union Government Fishery and Marine Biological Survey vessel S.S. " Pickle ". It was then ascertained that some three miles off the coast lay an area which was devoid of bottom fish life. The trawl contained considerable quantities of fish bones, and also dark green, evil-smelling mud, later identified as containing sulphuretted hydrogen.

Von Bonde (1928) and Marchand (1928) stated that:—

" The bottom samples from this area on the West Coast especially between the latitudes of 21° 30′ South and 24° 30′ South (approximately 200 miles) and extending 25 to 30 miles west (i.e. up to the 77-fathom line) are devoid of living animal and vegetable life. Evidences of dead fauna and flora, however, are numerous. For this reason the area is known as the azoic zone of the West Coast. The bottom samples from this region when brought to the surface have a green colour and are of a muddy consistency. The stench is unbearable and similar to hydrogen sulphide or the odour characteristic of putrefaction.

There is, however, a very narrow strip of grey sandy bottom close inshore about three miles wide on which marine fauna and flora abound.

As the outer limit of the azoic zone is approached, the percentage of diatomic skeletons decreases greatly while foraminifera increase. Near the westward edge of the azoic zone numerous empty shells of the bivalve *Crassatella africana* occur, whereas outside the azoic zone are live specimens which are frequently brought up in the trawl. On the western edge and beyond bottom samples have no smell and show evidence of marine fauna, e.g. worms, crustaceans, holothurians, etc. Trawling operations reveal rich hauls of Stockfish (*Merluccius capensis*), Kingklip (*Genypterus capensis*) and Soles (*Austroglossus microlepis*)."

This azoic zone extends approximately 200 miles in a direction parallel to the coast, and 30 miles in width, and is some 6,000 square miles in area (see Plate II). It has been only partially surveyed, and although no evidence of living animal and vegetable life was found on the sea bottom here by Von Bonde (1928) and Marchand (1928), the Danish Deep-sea Expedition in December, 1951, found evidence of living animals at two localities in this azoic area. In a private communication to the writer, Professors Spärck and Nielsen of the Danish Deep-sea Expedition ship " Galathea " stated that at two profiles (lines at right angles to the coast) at the latitudes of Sandwich Harbour and Conception Bay (see Plate II), a considerable number of animals [annelids (worms) and molluscs (shells)] were found in the green mud of the sea bottom. Moreover, two distinct age groups of these animals were observed. It is therefore probable that considerable changes have taken place since 1928.

It is, however, a fact that attempts at commercial bottom-fishing (trawling) operations in the azoic area have proved futile. Surface fish, however, abound in considerable quantities.

(*d*) Causes of the Mortality.

Mass mortalities are locally known as " sulphur eruptions ", and various theories have been suggested. The appearance of mud islands and sulphuretted hydrogen gas, as well as coastal sulphur deposits, have suggested the so-called volcanic theory.

The theory of underground rivers whose outlets are supposed to be situated in the sea-bed is also popular. Local inhabitants are of the opinion that shortly after rains have fallen in the hinterland a mass mortality of fish may be expected. Nearly all the rains inland, as well as coastal rains, are to a large extent associated with northerly winds, and this correlation with mass mortality has been suggested above in (*a*) of this section.

In recent years prominence has been given to the presence of poisonous plankton, i.e. the dinoflagellates *Gymnodinium* and *Gonyaulax*, as the cause of mass mortality. They are both normal components of oceanic plankton, and are present in very small quantities. During a " bloom " or mass production their number may exceed sixty million in a litre of sea-water, and the sea then displays a characteristic red colour. There are, however, many other types of marine plankton that discolour seawater, i.e. Noctiluca, the harmless luminescent flagellate, a ciliate protozoa of the *Mesondinium* species identified by Charles Darwin (1845) off the Valparaiso coast, and by Hart (1934) in the Cape seas. Certain sulphur bacteria also give the sea a reddish hue. The Red Sea derives its name from the small yellowish-red rafts of the alga *Trichodesmium*.

Brongersma-Sanders (1948) first suggested that the mass mortality in the Walvis region may be due to the dinoflagellate *Gymnodinium*. It was, however, not until December, 1950, that a chance visit of the Danish Deep-sea Expedition ship coincided with a mass mortality (a few days previously) when a small dinoflagellate of the *Glenodinium* species was actually identified in this region.

In a private communication, Professors Spärck and Nielsen stated:—

" On 25th December, 1950, the surface of the sea inside Walvis Bay, and also in the adjoining coastal waters, was covered to a considerable extent with a layer of what might be described as a thick brownish soup.

So dense were the organisms that, when the penetration of light was measured through this layer, 99 per cent. was obliterated at a depth of 0·6 metres. The approximate depth of this layer was about 1 metre, and consisted almost entirely of a small dinoflagellate of the *Glenodinium* species ".

There is no possible doubt whatsoever that during a " bloom " or mass production of these dinoflagellates extremely toxic neurotoxins are produced, and all fish in the proximity are killed. It will be shown later, however, that the permanent condition of the water layer adjacent to the sea bottom contributes to the mass destruction of fish life.

(*e*) The Bacterial Production of Sulphuretted Hydrogen on the Sea Bottom.

In a publication by the writer (1934) the presence of sulphate-reducing bacteria in bottom muds from the Walvis region was recorded. The development and growth of these micro-organisms, *Vibrio aestuari*, and subsequent production of sulphuretted hydrogen from sulphates in seawater, demand anaerobic conditions in the sea bottom. These conditions may be periodic. Previous to 1950 the distribution of oxygen in the water column above the floor of the sea in the Walvis region and its variation were unknown quantities. In order therefore to obtain a clearer picture of conditions here, it was decided to carry out further investigations. In May, 1950, the Division of Chemical Services arranged for a re-investigation of the problem of the mass mortality of fish in the Walvis region, and observations were made on certain chemical, physical, and biological factors. During these investigations further samples of bottom mud were also obtained and these were sent to Mr. K. R. Butlin of the Microbiological Division of the Scientific and Industrial Research Laboratories, Teddington, England. In a private communication, Mr. K. R. Butlin states:—

" Halophilic sulphate-reducing bacteria (*Desulphovibrio desulphuricans*) were readily isolated from the bottom samples of mud from this region, using a medium consisting of sea-water to which sodium lactate (0·3 per cent.), sodium sulphate (0·1 per cent.), and small quantities of phosphate, ammonium chloride and magnesium sulphate had been added. No accurate methods exist for estimating the concentration of sulphate reducers, but, with the techniques available, a viability count of 10^2 sulphate reducers/ml. was obtained. Recent experiments at Teddington have shown that this figure may well represent a real viability count of 10^7/ml. What can be stated with assurance is that conditions in the mud samples were very favourable for the development and sulphate-reducing activities of the bacteria. The particular strain which was isolated differed significantly in its morphology from " normal " strains, the cells being thinner and much more curved than the usual comma-shaped vibrios ". (See Plate VI.)

As will be shown later, conditions are probably favourable throughout the year for the production of considerable quantities of sulphuretted hydrogen.

(*f*) Sources of Information and Oceanographical Conditions, and the Work of the South West Africa Administration's Patrol Vessel " Namib ".

It is observed that the Walvis " azoic " region lies within the Benguela current (see Plate II). It is therefore necessary to examine briefly the oceanographical conditions of this current from existing records, and attempt to implement this data as necessary.

Data on the Benguela current are scanty, and information on bottom deposits, water temperatures, dissolved oxygen content, seasonal variation and sudden changes due to meteorological conditions are almost non-existent. Some relevant information was obtained from the Union Government's publications, the " Fisheries and Marine Biological Survey Reports ", as well as from the " Discovery " reports, and the " Meteor " publications. The oceanographical ship " Discovery " (British Colonial Office) and the German deep-sea Atlantic expedition ship " Meteor " both worked stations in the coastal waters off the west coast of South Africa.

References to previous papers dealing with mass mortality of fish at Walvis Bay and in other parts of the world are given by Brongersma-Sanders (1948).

Arrangements were made by the Division of Chemical Services and the Fishing Industry Research Institute with the South West Africa Administration, and their patrol vessel, " Namib ", was made available for a short period during May, 1950. This ship was not fitted with equipment for oceanographical work. Waterbottles, plankton nets and deep-sea thermometers were borrowed from the Union Division of Fisheries. A hand-driven Kelvin sounding-machine was acquired and 120 metres of thin flexible steel sounding wire

were fitted to the drum. A small laboratory was kindly made available at Walvis Bay and this was fitted out with chemical apparatus. Standard solutions were brought from Cape Town. Samples were obtained from 16 different stations in the vicinity of Walvis Bay (see Plate V). Ninety-seven estimations of dissolved oxygen, pH and salinity were carried out from surface and subsurface samples of water. A number of samples of bottom water was examined for dissolved sulphuretted hydrogen. Bottom mud was collected and analysed, and additionally 18 catches of surface plankton were obtained and dominant phytoplankton identified.

SECTION V.

(*a*) The Normal Condition of Dissolved Oxygen and Sulphuretted Hydrogen in the Water of the Azoic Zone.

It is considered that normal conditions prevail in this region throughout the year except at such times as a mass mortality is pending, occurs, or has just taken place (see Plate VII).

Previous to the visit of the writer in May, 1950, the last mass mortality occurred in March that year. The analytical work carried out in May, 1950, is shown in Appendix " B ", and a typical result (Station 16) is given in column A of Table V below.

Some four months later, dissolved oxygen was also estimated in the vicinity of Station 16. This was made possible by the courtesy of the Chief Scientist in R.R.S. " William Scoresby ".

A. " Namib " Station 16:—

Date: 22/5/50.
Time: 1430.
Wind: S.W. 4–6 knots.
Position: Lat. 22° 52·3′ S.
Long. 14° 19·6′ E.
Sounding: 77 metres, azoic mud.

B. " William Scoresby " Station 1076:—

Date: 29/9/50.
Time: 1033.
Wind: light airs to calm.
Position: Lat. 22° 52′ S.
Long. 14° 20′ E.
Sounding: 69 metres, azoic mud.

The oxygen and sulphuretted hydrogen figures are in millilitres/litre.

TABLE V.

Depth (metres).	A.			B.		
	Temp.	O_2.	H_2S.	Temp.	O_2.	H_2S.
0.....	14·9	4·80	—	11·9	3·51	—
10.....	13·4	3·61	—	11·5	3·19	—
20.....	12·9	1·76	—	11·5	2·91	—
30.....	12·6	1·26	—	11·5	2·86	—
40.....	12·5	0·52	—	11·1	1·81	—
50.....	12·3	0·40	—	11·0	1·68	—
60.....	12·2	0·04	—	11·0	0·21	—
64.....	—	—	—	11·0	0·06	0·02
70.....	12·2	0·02	—	—	—	—
76.....	12·2	0·00	5·88	—	—	—

The above figures clearly indicate in both cases a steady diminution of dissolved oxygen content from the surface down to the sea-bed. Every subsurface sample of water was examined qualitatively for dissolved sulphuretted hydrogen. The 76-metre sample was the only one that gave positive tests. Quantitative analysis was carried out shortly afterwards. It must be stated that all samples of water examined for dissolved oxygen were first tested for the presence of sulphides. Only samples that contained no sulphuretted hydrogen, and appeared clear, i.e. free from bottom deposits, were examined for oxygen.

Table VI shows results from five other stations outside Walvis Bay (see Chart No. 2 for positions), to indicate the thickness of the layer adjacent to the sea-bottom containing less than 1 millilitre of dissolved oxygen.

TABLE VI.

Stations.	3.	4.	10.	11.	12.
Sounding in metres.	72	78	43	66	58
Water column containing 1 ml. or less of dissolved oxygen	72–52 metres	78–51 metres	43–31 metres	66–42 metres	58–41 metres
Percentage of water column containing 1 millilitre or less.	28	35	28	36	29

Tables V and VI above reflect the extremely low oxygen content in the water adjacent to the sea-bottom.

The pH of surface and subsurface water samples varied from 8·0 at the surface to 7·6 in the deep samples.

The water samples taken just above the sea-bed gave positive tests for sulphuretted hydrogen at some stations. Quantitative results were from a trace to 6·1 millilitres per litre according to the locality.

Every bottom sample procured (Stations 1–16) contained sulphuretted hydrogen. The mud was of a soft slimy consistency which blackened bright copper equipment. Core bottom samples were obtained by means of a weighted tube.

ANALYSIS.

These samples were taken at " Namib " stations (see Chart No. 2):—	*Percentage.*	*Station No.*
(*a*) Water at 105° C.	83·3	12
Analysis on water-free samples—dried at 105° C.		
(*b*) Loss 105° C–160° C.	less than 1	8–11, 13, 16
(*c*) Loss on Ignition 160° C–600° C (average)	14·1	8, 9, 10
Loss on Ignition 160° C–600° C.	16·9	11
Loss on Ignition 160° C–600° C.	9·9	13
Loss on Ignition 160° C–600° C.	18·7	16
(*d*) Phosphate as P. (average)	0·140	8, 9, 10
Phosphate as P.	0·135	11
Phosphate as P.	0·102	13
Phosphate as P.	0·182	16
(*e*) Protein (N x 6·25)	2·7	8, 9, 10
Ether extraction	0·12	8, 9, 10
(*f*) Arsenic (parts per million)	12·0	8

(*g*) The following elements were found to be present (spectrographic analysis): Silicon, Magnesium, Calcium, Iron Aluminium, Titanium, Copper, Boron, Cadmium, Vanadium, Antimony and Hafnium.

(*h*) Calcium Carbonate was not detected.

(*i*) Chlorophyll: This estimation was recently carried out by Brongersma-Sanders (1951) who returned a figure of 7·5 milligrams per 100 grams of air-dried sediment.

(*j*) Texture (sedimentation method): Principally fine silt, i.e. particles between 0·02–0·002 mm. diameter.

(*k*) Carbohydrate: Analysis for carbohydrate by the combustion method did not give concordant results. Preliminary investigations by Dr. J. R. Nunn indicate that carbohydrates are present.

The composition of the bottom " azoic " deposit consists for the most part of the siliceous skeletal remains of diatoms. For dominant species see a former publication by the writer (1934).

(*b*) The Abnormal Condition of Dissolved Oxygen and Sulphuretted Hydrogen in the Water of the Azoic Zone.

The R.R.S. " William Scoresby " had the good fortune to visit Walvis Bay on the 7th and 8th March, 1950, when small quantities of dead and dying fish were observed in the water and on the beaches between Walvis Bay and Swakopmund. Mortality of fish continued during the period March 8th to 13th. The ship steamed from the open sea on a profile of latitude 22° 44′ South and commenced her first station (Station 976) about 160 miles offshore in 3,100 metres. The water column at this station has dissolved-oxygen figures from 5·37 millilitres/litre at the surface to 4·52 millilitres/litre at a depth of 3,098 metres. The next station, 977 at 120 miles offshore, depth 1,600 metres, again displayed normal dissolved-oxygen content, except at 300 metres where a figure of 0·91 millilitre/litre was observed. Indications of this tongue of low-oxygen content water was again apparent at the next station, 978, at 400 metres. At Station 979, depth 139 metres, the lowest figure of 1·18 for dissolved oxygen in the water column was at 100 metres. Here, as at the next station, 980, 28 miles offshore, a steady decrease from the surface, 6·43, to the 50-metre depth, 0·13 millilitre/litre, and a slightly higher figure, i.e. 0·37 millilitre/litre at 100 metres, were observed. At Station 981, depth 64 metres, the entire water column contained less than 1 millilitre of dissolved oxygen, the surface figure being 0·33 millilitre/litre. The dissolved-oxygen figures and water temperatures are shown in Plate VIII. The increases in temperatures should also be noted.

(*c*) Sulphuretted Hydrogen in Sea Water.

There is no doubt that in the problem of the mortality of fish in the Walvis region, attention must be centred on the important factor of sulphur. The sulphur in the sea water runs the gamut of changes from sulphate to complete reduction, and then again to complete oxidation—$SO_4 \rightarrow H_2S \rightarrow S \rightarrow SO_4$. It should be noted that during the oxidation of sulphuretted hydrogen back to sulphate, a considerable amount of dissolved oxygen is removed from the sea water. The " milky " sea water often observed in the sea in and around Walvis Bay may be due to colloidal sulphur formed by the oxidation of sulphuretted hydrogen.

(*d*) General Observations.

At the " William Scoresby " Stations Nos. 988 and 989, latitude 25° 12′ South, patches, or possibly an extension, of azoic mud were found, and the water column again exhibited decreasing dissolved-oxygen content from 7 millilitres/litre at the surface to 0·30 millilitre/litre at the 20-metre zone near the bottom. Green sulphide diatomaceous ooze is found inside Walvis Bay and extends northwards for some ten miles along the coast beyond the precincts of the Bay at about one mile from the beach. At " Namib " Station 6, one mile from the shore, inside the Bay near Pelican Point (see Chart No. 2), this sulphide ooze extended up to the breakers, i.e. within 30 feet of the shore. At low tide the smell of sulphuretted hydrogen was observed. The only forms of marine life visible in the water near the beach were a few crabs and some polychaete worms of the family Sabellidae. Sea water taken from near this beach gave 3·40 millilitres/litre dissolved oxygen and another surface sample about half a mile from the shore 3·23 millilitres/litre of oxygen. Oxygen from water in the breakers on the seaward side of Pelican Point gave 5·51 millilitres/litre.

In section 1 (*e*), it was noted that the eastern line of demarcation of the azoic mud was about three miles from the breakers, the edge of the mud running approximately parallel with the coast. The surface and bottom layers of this narrow strip are well oxygenated. Breaker action, especially in heavy weather, is an important factor in this oxygenation.

SECTION VI.

(*a*) Stagnant Conditions and Depletion of Dissolved Oxygen in Other Parts of the World.

It is interesting to compare other localities where the dissolved oxygen in the lower layers of the sea is depleted.

(i) *The Black Sea.*

The Black Sea is separated from the Mediterranean by a shallow sill, and a permanent biological climax is reached. Here the organic matter dropping on the sea bed from the productive surface layers absorbs the dissolved oxygen in the bottom water and anaerobic conditions are established. When these conditions prevail, the anaerobic sulphate-reducing bacteria flourish, and the production of sulphuretted hydrogen proceeds. Without the scavenging or ventilating action of the open sea, the layer of water in which the dissolved oxygen has been depleted, gradually increases. Eventually a boundary is attained, below which there is no dissolved oxygen. The line of demarcation is variable, and depends on the dissolved oxygen at the air/water surface plus oxygen derived from photosynthesis in the euphotic zone.

It is stated by Sverdrup, Johnson and Fleming (1946) and Nikitin (1931) that in the Black Sea a toxic layer of water extends upwards from the bottom and is approximately 1800 metres in thickness, the lower limit of animal life being about 130–190 metres.

(ii) *The Humboldt or West Coast Current of South America.*

The Humboldt current flows northwards off the west coast of South America from about 36° South to about 4° South. It is about 1800 miles in length and has very many features in common with the Benguela current. According to Gunther (1936) a reversal brings warm equatorial water southwards along the coast of Peru. This counter-current is known by local fishermen as "El Nino," meaning " The Child." It is most noticeable after Christmas, and is a seasonal occurrence of varying severity, and happens usually during the months of January to March. Northerly winds and heavy rains are associated with this hot counter-current. In some years this brings havoc on a coast that normally enjoys a dry climate. In the sea the effects are equally disastrous. Fish and lesser forms of life are killed by the sudden rise of temperature. Bird life is affected by this loss of food [compare this with Morrell (1843) concerning the dead seals on Possession Island]. It is noted therefore that the time of the year of northerly winds, invasion of oceanic water and mortalities of fish in the Humboldt current correspond to the phenomena in the Benguela current in the Walvis region.

Falke (1950) describes the mortality of fish at Conception Bay, Chile, and compares this with mass destruction of fish in other parts of the world, e.g. South California, Peru, Mexico, Florida, Delaware Bay, Dakar, Walvis, Japan, Malabar, and the Arabian coasts bordering on the Red Sea. He considers that under certain conditions it is possible that large masses of foreign plankton, together with local organisms, perish at regular intervals. Besides sulphuretted hydrogen, poisoning by dinoflagellates (" red water ") is probably one of the most important factors in starting the phenomenon. If a strong production of sulphuretted hydrogen and redwater takes place, azoic regions may be formed temporarily for some months only, i.e. the annihilation of a regional fauna and the recolonization may take place at regular intervals within short periods.

(iii) *Norwegian Fjords.*

Strom (1936) in his investigation of the hydrography and bottom deposits of badly ventilated Norwegian fjords, found that when bottom waters of a basin stagnate for any length of time as a result of oxidation processes, the lower layers become depleted of oxygen. It is interesting to compare Strom's figure for Lenefjord with those of " Namib " Station 16 (see column "A" of Table V on page 12).

Lenefjord, June 6, 1933; depth 220 metres.

Depth (metres).	Temp. °C.	S‰.	O_2 ml/l.	pH.
1.....	17·4	27·72	6·05	8·0
20.....	6·2	31·65	4·98	7·4
40.....	5·5	32·09	0·55	7·2
215.....	5·3	32·36	0·0	7·1

The resemblance between the stagnant conditions in a fjord (basin conditions) and the open sea (Walvis region) is striking. In addition, the layer of water immediately next to the bottom contained sulphuretted hydrogen—Norwegian fjord 1·05 millilitres/litre and Walvis region 5·88 millilitres/litre. In the case of the Norwegian fjords known as " threshold " fjords, a shallow sill prevents exchange between the bottom water and the open sea. An influx of fresh water (see salinity at 1 metre in Lenefjord) induces stratification.

SECTION VII.

(*a*) *The Walvis Ridge.*

At the northern boundary of the Benguela current near Cape Frio, there is an extensive bank or ridge that runs obliquely towards the mid Atlantic at an angle of about 30 degrees from the coast, and joins the so-called Atlantic ridge. Gough Island and the Tristan da Cunha group are regarded as " peaks " that emerge above the surface of this submarine mountain range. Its significance in our problem lies in the fact that it forms a natural barrier, or possibly a sill between the deep water of the Atlantic on the northern and southern sides (see Plate IX).

(*b*) Summary and Conclusions.

(1) Almost every year a mass mortality of fish takes place in the Walvis region, South West Africa. These mortalities usually occur during December or January, but the period may sometimes extend to March.

A correlation exists between certain meteorological and oceanographical conditions and the appearance of the dead fish.

(2) Off the coast of South West Africa is a permanent area of approximately 6,000 square miles where the sea bottom is characterised by a sulphide diatomaceous ooze. This constitutes the so-called " Azoic Zone ", lies between latitude 21° 30′ South and 24° 30′ South, and extends approximately from the 150-metre bottom contour to the 50-metre bottom contour, the latter being about three miles off the land. A broad tongue of this sulphide ooze is also found on the sea bottom of Walvis Bay.

(3) The cold Benguela current flowing northwards over this bottom deposit is rich in nutrient salts and is well seeded with phytoplankton. In this environment, together with abundant sunshine, an extremely productive region results. This rich plankton (consisting of coastal and antarctic types) supplies the food for a vast quantity of surface fish, the principal varieties being the Pilchard (*Sardinops ocellata*), and the Maasbanker (*Trachurus trachurus*), bottom fish being extremely scarce or unknown.

(4) With the sudden onset of winds from north to west, the normal directional flow of the Benguela current is retarded or even reversed, and considerable masses of sub-tropical Atlantic Ocean highly saline water invade the coastal region. This results in surface temperatures being elevated from 13° to 24° C. on occasion. Increases of 5–6° C are, however, more commonly experienced. These sudden increases of temperature and salinity bring about a destruction of the coastal plankton. Oceanic types of plankton and fish now temporarily inhabit the coastal waters.

(5) The " azoic zone " is thus augmented from time to time with organic matter in the form of dead plankton and higher forms of marine life that are destroyed by sudden chemical and physical changes.

As the bottom deposit is in an extremely fine state of division [see Section V (*a*), Texture], it is implied that here bottom currents must be feeble, and moreover there is a tendency for this marine deposit to accumulate and thus a narrow layer of stagnant water is formed in the open sea.

Once these conditions are established, the dissolved oxygen becomes depleted, and in this anaerobic environment sulphate-reducing microorganisms flourish, and the production of sulphuretted hydrogen ensues. If these conditions are not disturbed, so much sulphuretted hydrogen is produced that the lower layers of the water column become even more depleted in dissolved oxygen, and may exhibit evidence of dissolved sulphuretted hydrogen. Under certain meteorological conditions the bottom water may be forced up from the shelving sea bottom to the surface and surface fish will be killed.

(6) The boundaries of the "azoic zone", i.e. the permanent large area of sulphide diatomaceous deposit, fluctuate and depend on the quantity of dissolved oxygen and the speed of the bottom current. The rate at which dissolved oxygen can contact the bottom deposit controls the oxidation of sulphuretted hydrogen and also the oxidation of organic remains of plankton, thus decreasing or increasing the periphery of the "azoic zone". Apart from the usual factors governing the dissolved oxygen in the sea, the action of breakers and waves on sandy beaches and rocky ledges must be stressed. This ensures that the narrow strip from the shore three miles to seaward is well oxygenated, resulting in an abundance of marine life and bottom fish in this inshore band.

(7) The occurrence of poisonous plankton is also an important factor in the mass mortality of fish in this region. It is not known at present if poisonous dinoflagellates are brought in to the coast by the invasion of subtropical oceanic water, or if they are normally present in the coastal and antarctic plankton.

It is apparent, however, that in this fertile environment, under certain conditions, a "bloom" or mass production of dinoflagellates belonging to the *Gymnodinium* or allied species, occurs, and fish in this proximity will be destroyed.

(8) The complexity of the problem of the mass mortality of fish in the Walvis region should not be underrated. Although the permanent lack of dissolved oxygen in the bottom layers of the water column in the open sea has been stressed, it is not clear whether mortalities are caused by—

(*a*) anoxia;
(*b*) anoxia plus sulphuretted hydrogen poisoning;
(*c*) poisonous plankton;

or combinations of the above.

(ii) Opsomming en Gevolgtrekkings.

(1) Byna elke jaar vind daar 'n massasterfte onder die vis in die Walvisbaai-omgewing plaas. Hierdie sterfte kom gewoonlik gedurende Desember en Januarie voor, maar die periode kan soms tot Maartmaand strek.

Daar bestaan 'n korrelasie tussen die verskyning van die dooie vis en sekere meteorologiese en oseanografiese omstandighede.

(2) Net weg van die Suidwes-Afrikaanse kus af is daar 'n permanente gebied van ongeveer 6,000 vierkante myl waar die seebodem deur 'n sulfiede-diatomeëslik gekenmerk word. Dit maak die sogenaamde asoïese streek uit en lê tussen 21° 30′ en 24° 30′ suidelike lengtegraad en strek ongeveer van die 150-meter-bodemkontoer tot die 50-meter-kontoer. Laasgenoemde is ongeveer 3 myl van die land af. 'n Breë tongvormige gebied van hierdie sulfiedeslik is ook op die seebodem van Walvisbaai te vind.

(3) Die koue Benguela-stroom wat noordwaarts oor hierdie bodemafsaksel vloei, is ryk aan voedingsoute en is ook goed voorsien van plantaardige plankton. In hierdie omgewing, voorsien van volop sonskyn, ontstaan daar dus 'n hoogs produktiewe gebied. Hierdie plankton (bestaande uit sowel kus- as antarktiese tipes) verskaf die voedsel vir geweldige groot hoeveelhede oppervlaktevissoorte, bestaande hoofsaaklik uit die Sardyn (*Sardinops ocellata*) en die Marsbanker (*Trachurus trachurus*). Diepwatervis is baie skaars of onbekend.

(4) Met die skielike ontstaan van winde vanuit die noorde tot die weste word die normale vloei van die Benguela-stroom vertraag of selfs omgeswaai, en groot massas water van hoër soutgehalte van die subtropiese Atlantiese Oseaan stroom die kusgebied binne. As gevolg hiervan styg die temperatuur van die oppervlakte soms van 13° C. tot 24° C. Stygings van 5–6° C. is egter meer normaal. Hierdie skielike verhogings van die temperatuur en soutgehalte veroorsaak die dood van die kustipes plankton terwyl die oseaan-tipes en vis nou tydelik die kuswaters bewoon.

(5) Die asoïese streek word dus van tyd tot tyd aangevul deur organiese stowwe in die vorm van sowel dooie plankton as hoër vorms van marinelewe wat as gevolg van die skielike chemiese en fisiese veranderings omkom.

Aangesien die bodemafsaksel in 'n besondere fyn toestand verkeer [sien afdeling V (*a*), Tekstuur], word afgelei dat strome op die bodem baie swak moet wees, en boonop is daar 'n neiging vir die marine-afsaksel om op te gaar. Sodoende ontstaan daar 'n smal laag stilstaande water in die oop see.

Wanneer hierdie toestande ontstaan raak die opgeloste suurstof op, en in so 'n anerobiese omgewing floreer die sulfaat-reduserende mikro-organismes met die gevolg dat swawelwaterstof gevorm word. Indien hierdie omstandighede ongestoord voortgaan, versamel soveel swawelwaterstof dat die onderste lae van die water nog laer in suurstofgehalte raak en selfs die eienskappe van opgeloste swawelwaterstof vertoon. Onder sekere meteorologiese omstandighede kan hierdie bodemwater van die seevloer na die oppervlakte geforseer word, en onder sulke omstandighede word die oppervlaktevis gedood.

(6) Die buitelyne van die "asoïese omgewing" wissel, aangesien dit afhang van die hoeveelheid opgeloste suurstof en die snelheid waarmee die bodemstroom beweeg. Die snelheid waarmee die

opgeloste suurstof in aanraking met die afsaksel op die bodem kom, bepaal die oksidasie van die swawelwaterstof, asook dié van die organiese oorblyfsels van die plankton, en sodoende vermeerder of verminder die omvang van die asoïese streke. Afgesien van die gewone faktore wat die hoeveelheid opgeloste suurstof in die see beïnvloed, moet die invloed van branders en brekers op sanderige en rotsagtige kusstroke nie uit die oog verloor word nie. Hierdie faktore verseker dat die nou strook (van die kus af tot drie myl seewaarts) goed voorsien is van suurstof, wat tot 'n oorvloed van marinelewe en bodemvis in die kusstrook lei.

(7) Die aanwesigheid van giftige plankton is ook 'n vername faktor in die massasterfte onder vis in hierdie omgewing. Dit is nog nie bekend of giftige dinoflagellata na die kus gevoer word deur subtropiese seestrome, en of hulle normalerwys in die kus- en antarktiese plankton aanwesig is nie.

Dit is egter vanselfsprekend dat in hierdie vrugbare omgewing 'n massa-produksie van dinoflagellata behorende tot die *gymnodinium* of verwante soorte onder sekere omstandighede voorkom, en dat vis in die nabyheid daarvan sal doodgaan.

(8) Die ingewikkeldheid van die probleem van die massasterfte van vis in die Walvisbaai-gebied mag nie onderskat word nie. Alhoewel nadruk gelê is op die permanente tekort aan opgeloste suurstof in die onderste lae van die wâter in die oop see, is dit egter nog nie duidelik of die sterfte te wyte is aan—

(*a*) suurstof-tekort;
(*b*) suurstof-tekort plus swawelwaterstof-vergiftiging;
(*c*) giftige plankton;

of 'n kombinasie van hierdie faktore nie.

(iii) Zusammenfassung und Schlussfolgerungen.

(1) In der Umgebung der Walfischbucht, Südwest-Afrika, findet fast jedes Jahr ein Massensterben von Fischen statt; dieses Sterben tritt gewöhnlich im Dezember oder Januar auf, kann sich aber bis zum März hinziehen.

Es bestehen Beziehungen zwischen gewissen meteorologischen und ozeanographischen Bedingungen und dem Auftreten toter Fische.

(2) Der Küste von Südwest-Afrika vorgelagert ist ein Gebiet von annähernd 6,000 Quadratmeilen, in dem der Meeresboden aus einem Diatomeenschlamm besteht, der dauernd Schwefelwasserstoff entwickelt (Faulschlamm). Dies ist die sogenannte "azoische Zone"; sie liegt zwischen 21° 30′ und 24° 30′ südlicher Breite und reicht etwa von der 150-Meter bis zur 50-Meter-Tiefenlinie, die letztere ungefähr 3 Meilen vom Lande entfernt. Eine breite Zunge dieses Faulschlammes findet sich auch auf dem Boden der Walfischbucht.

(3) Der kalte Benguela-Strom, der diese Ablagerung in nördlicher Richtung überströmt, ist reich an Nährsalzen und gut mit Phytoplankton besiedelt. Unter diesen Umständen, noch dazu mit reichlicher Sonnenbestrahlung, wird die Planktonproduktion ausserordentlich gesteigert. Dieser Planktonreichtum, aus Küsten- und antarktischen Formen bestehend, liefert die Nahrung für eine grosse Menge an der Oberfläche lebender Fische, vorherrschend Pilchard (*Sardinops ocellata*) und Maasbanker (*Trachurus trachurus*), während am Boden lebende Fische äusserst selten oder unbekannt sind.

(4) Durch das plötzliche Einsetzen nördlicher bis westlicher Winde wird der normale Lauf des Benguela-Stromes aufgehalten oder sogar umgekehrt, und beträchtliche Mengen subtropischen Atlantikwassers mit hohem Salzgehalt dringen in das Küstengebiet ein. Dies hat zur Folge, dass die Oberflächentemperatur gelegentlich von 13° C. bis auf 24° C steigt, Zunahmen von 5–6° C sind indessen häufiger. Diese plötzliche Steigerung von Temperatur und Salzgehalt vernichtet das Küstenplankton, und Hochseeformen von Plankton und Fischen bewohnen nun zeitweilig die Küstengewässer.

(5) Die "azoische Zone" wird auf diese Weise von Zeit zu Zeit angereichert mit organischer Substanz in Form von totem Plankton und höheren Organismen, die durch plötzliche chemische und physikalische Veränderungen vernichtet worden sind.

Da die Ablagerung am Meeresboden aus ausserordentlich fein verteiltem Material [siehe Teil V (*a*), Struktur] besteht, ist anzunehmen, dass Strömungen am Meeresbodem hier schwach sein müssen; ausserdem zeigt diese Meeresablagerung eine Tendenz, durch Anhäufung eine dünne Schicht stagnierenden Wassers in der offenen See zu bilden.

Wenn dieser Zustand eingetreten ist, wird der gelöste Sauerstoff stark verringert; in dem sauerstoffreien Medium gedeihen Sulphat reduzierende Mikroorganismen üppig, und die Entwicklung von Schwefelwasserstoff beginnt. Wenn dieser Zustand nicht gestört wird, wird soviel Schwefelwasserstoff entwickelt, dass in den unteren Schichten der Wassersäule der Gehalt an gelöstem Sauerstoff noch mehr vermindert wird und sogar gelöster Schwefelwasserstoff auftreten kann. Unter gewissen meteorologischen Bedingungen kann dieses Wasser aus grösseren Tiefenstufen an die Oberfläche getrieben werden, und die an der Oberfläche lebenden Fische gehen zu Grunde.

(6) Die Grenzen der " azoischen Zone ", d.h. des grossen Gebietes der ständigen Ablagerung von Diatomeen-Faulschlamm, schwanken; sie hängen von der Menge gelösten Sauerstoffs und der Geschwindigkeit der Bodenströmung ab. Von der Menge gelösten Sauerstoffs, die in gleichen Zeitabschnitten mit der Ablagerung am Meeresboden in Berührung kommt, hängt die Oxydation des Schwefelwasserstoffs und ebenso die Oxydation organischer Planktonreste ab; die Grenze der azoischen Zone wird entsprechend zurück- oder vorgeschoben. Neben den Faktoren, die gewöhnlich den Gehalt des Meerwassers an gelöstem Sauerstoff regeln, muss die Wirkung von Brechern und Wellen am sandigen Strand und an Felsbändern besonders betont werden. Hierdurch wird sichergestellt, dass die schmale, 3 Meilen breite Zone längs der Küste einen hohen Sauerstoffgehalt aufweist, der küstennahe Teil des Stromes ist infolgedessen überreich an Lebewesen, auch an am Boden lebenden Fischen.

(7) Das Vorkommen von giftigem Plakton ist auch ein wichtiger Faktor beim Massensterben von Fischen in diesem Gebiet. Es ist z.Z. unbekannt, ob giftige Dinoflagellaten durch das Eindringen subtropischen Hochseewassers an die Küste gebracht werden, oder ob sie normalerweise im Küsten- und antarktischen Plankton vorhanden sind.

Es ist indessen augenscheinlich, dass in diesem reichen Lebensraum unter gewissen Bedingungen eine " Wasserblüte " oder Massenproduktion von Dinoflagellaten (*Gymnodinium* oder verwandte Formen) auftreten kann, und Fische in der Nachbarschaft zu Grunde gehen.

(8) Das Massensterben von Fischen in der Umgebung der Walfischbucht ist ein verwickeltes Problem, das nicht unterschätzt werden sollte. Obwohl der ständige Mangel an gelöstem Sauerstoff in den Bodenschichten der Wassersäule in der offenen See besonders hervorgehoben wurde, ist es nicht sicher, ob das Sterben verursacht wird durch—

(a) Sauerstoffmangel;
(b) Sauerstoffmangel, verbunden mit Schwefelwasserstoffvergiftung;
(c) giftiges Plankton;

oder durch Zusammenwirken dieser Faktoren.

SECTION VIII.

ANNEXURES.

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(*c*) Appendices.

Appendix I. —A. General Conditions at Walvis Bay.
B. Statements by Observers.

Appendix II. —A. Station List—Patrol Vessel " Namib ".
B. Dominant Phytoplankton, Walvis Bay.
C. St. Helena Bay Phytoplankton.

Appendix III.—Station List—R.R.S. " William Scoresby ".

APPENDIX I.

A.—GENERAL CONDITIONS AT WALVIS BAY.

As stated in Section V on page 14, green sulphide diatomaceous ooze is found inside Walvis Bay. During oceanographical work with the patrol vessel " Namib ", it was noticed that after anchoring in the bay the anchor and portion of the cable invariably came up with adhering ooze, and a strong smell of sulphuretted hydrogen was in evidence. The anchor and portion of the cable lying on and near the bottom were discoloured black.

On all occasions when movements of shipping took place in the harbour and the bottom was stirred up, sea-breezes blowing shorewards frequently carried a smell of sulphuretted hydrogen perceptible a mile away.

During the movements of a large tug early one morning, the white paintwork discoloured and assumed a greyish black hue. The white paint in the proximity of the engine room and boilers was not affected—presumably the paint here was not covered with a film of moisture. After a few hours the discolouration disappeared.

Ghost Patterns.

The writer was informed by the magistrate of Swakopmund, that during a period of mass mortality of fish a few years ago, a fairly strong smell of sulphuretted hydrogen was in evidence in his house. The white paintwork in the rooms became discoloured, while in several of the rooms distinct patterns of white paint on the walls remained apparently unaffected. These patterns were silhouettes of furniture and picture frames, including the cord lines above the pictures—where the furniture had previously stood or where pictures had previously been hung. After a while, with the oxidation of the lead sulphide, the patterns vanished.

Bronze statues at Swakopmund in May 1950 displayed evidence of sulphide films, from sulphuretted hydrogen in the atmosphere about six months previous.

B.—Statements by Observers.

1. *Skipper of Local Fishing Boat* (*C.F.*).—Fifteen years experience fishing from Walvis Bay.

Just before an " eruption ", the sea turns a milky colour and the temperature of the water rises. The colour of the sea then changes to a light brown (khaki) eventually becoming coffee brown. It then stinks.

Many dead fish are seen floating around just before the appearance of milky water and small bubbles of stinking gas coming up from the bottom are noticed eight to ten miles from the shore. Inside Walvis Bay bubbles are bigger. During these changes of colour of the sea, fish are observed darting about gasping and struggling to get their heads out of the water. Later their struggles become feeble, and finally all movement ceases and they die.

Two or three days after an " eruption " the warm water continues and Cape fish like geelbek and elf may be caught—these fish are not normally found in this region.

2. *Skipper of a Steam Trawler* (*O.J.*).—This Skipper has a B.O.T. Certificate and had a Commission (Lieutenant) in the S.A. Navy during World War II. Eighteen years experience on this coast particularly between Walvis and Luderitzbucht.

Bubbles of gas at certain times arise from the sea bottom and these have not always an unpleasant smell. Only during an " eruption " is this so. Patches of discoloured water are noticeable most times half a mile to one mile south of Sandwich Harbour, the colour being milky to khaki green.

At Pelican Point, between changes of the tide, similar patches of discoloured water are seen, and the smell of sulphuretted hydrogen is apparent. These conditions are common throughout the year.

Before an eruption the weather is usually calm, and shoals of pilchards have been observed swimming in the surface water, their mouths wide open and their gills distended.

After the calm, northerly winds usually blow, and the surface temperature increases considerably. The water now looks dirty (with suspended matter) and the smell of sulphuretted hydrogen is noticeable even when fifteen miles out to sea. White paintwork and brass are discoloured grey-black.

I have seen " red " water sometimes, not always, during an eruption. These red patches are so dense that they may be lifted out by hand and the organisms cling together like lumps of congealed blood.

Long lanes of yellow brown streamers on the surface of the sea stretching out for miles are, however, very common. Phosphorescence is particularly brilliant during this period.

I have seen thousands of dead fish during a bad " eruption " as far south as Hollams Bird Island.

Sea birds are scarce, and do not eat dead fish although fresh. They may be seen diving into a fringe of blue water near the shore just outside the breakers.

I've never heard of anyone suffering from illness after eating gasping fish collected from the surface.

After a spell of northerly wind has been blowing, it is surprising how long the southerly current persists, even during light northerly winds.

3. *Deep Sea Diver and Local Resident* (*J. B. and F. B.*).—In January, 1949, we witnessed an unusual submarine disturbance in the area of water close to the slipway in Walvis Bay. Numerous bubbles came to the surface followed by clots of mud in many cases a foot in diameter. These then broke into small pieces. An unpleasant smell was noticed.

On another occasion while a tanker was berthing and the bottom mud was stirred up, hundreds of soles suddenly came up to surface near a sandy patch. Many people came down to the beach and speared them and filled baskets. They seemed perfectly edible.

4. *Dr. C. J. Molteno*.—During December, 1949, I visited Walvis Bay, During the second half of the month, while bathing in the sea about two miles to the eastward of Pelican Point, I observed that the temperature of the sea had risen considerably. I should say it was about 70° F. The weather at the time was calm but previous to this a northerly wind had been blowing. Such conditions prevailed also during January, 1950, when the sea temperatures were even higher, i.e. 78° F. (25·6° C.) (thermometer reading).

Fishing boats reported that numerous flying fish were seen about ten miles out to sea from Walvis, and I saw many specimens of Angola sardines (*Sardinella aurita*) in their catches.

APPENDIX II.

A.—STATION LIST: PATROL VESSEL "NAMIB".

Station.	Position.	Date. Hour.	Sound. Metres.	Wind. Force.	Sea.	Weather.	Depth Metres.	Temperature. Sea.	Temperature. Air.	pH.	O_2 ml/l.	H_2S ml/l.	Remarks.
—	Pelican Point Lighthouse.....	13/5/50 0800	—	N.E. 0–1	—	Dense fog 50 yards and less	—	—	—	—	—	—	Weather conditions from Pelican Point Lighthouse Met. Station.
		1800	—	S. 7–10	—								
—	Pelican Point Lighthouse.....	14/5/50 0800	—	S. 4–6	Sea slight Swell slight	Cloud overcast, visibility 1	—	—	—	—	—	—	Weather conditions from Pelican Point Lighthouse Met. Station.
		1800	—	S.W. 4–6	Sea moderate Swell moderate	Cloud, 3/8 Visibility 5–10	—	—	—	—	—	—	
1	Lat. 22° 52·2′ S.... Long. 14° 28·9′ E.	15/5/50 1500	20	S.S.W. 11–16	Sea slight Swell slight	Cloud 3/8 Visibility 5–10	0	14·3	—	8·0	5·80	—	—
							5	13·2	15·5	7·8	4·28	—	—
							12	12·9	15·5	7·7	1·17	—	—
							15	12·7	15·2	7·6	0·73	—	—
							18	12·8	15·9	7·6	0·52	—	—
							19	12·7	17·2	7·6	0·00	—	—
2	Lat. 22° 52·7′ S.... Long. 14° 27·9′ E..	15/5/50 1600	18	S.S.W. 11–16.	Sea slight Swell slight	Cloud 3/8.... Visibility 5–10	—	—	—	—	—	—	—
							16	—	—	—	0·12	—	—
							17	12·5	15·0	7·6	0·00	3·60	—
3	Lat. 22° 53·4′ S.... Long. 14° 21·2′ E..	16/5/50 1315	72	S.S.W. 10–12	Sea slight Swell moderate Visibility 5–10	Dense fog a.m. Clearing p.m.	0	13·9	—	8·0	4·27	—	—
							50	12·4	14·1	—	0·24	—	—
							60	12·2	13·6	7·8	0·27	—	—
							70	11·8	13·1	7·8	0·15	—	—
4	Lat. 22° 53′ S..... Long. 14° 17·4′ E...	16/5/50 1530	78	S.S.W. 10–12.	Sea slight. Swell moderate Visibility 5–10	Dense fog a.m. Clearing p.m.	0	14·1	—	8·0	3·78	—	Surface phosphate 0·03 mg-atoms P/M^3.
							50	12·3	14·9	7·8	2·90	—	
							60	12·2	14·6	7·8	0·75	—	
							70	12·1	14·0	7·7	0·18	—	
							77	12·2	15·1	7·6	0·09	—	
5	—	—	—	—	—	—	14·4	—	—	—	—	—	Samples of plankton and bottom mud only.
6	Lat. 22° 53·5′ S ... Long. 14° 26·7′ E..	17/5/50 1000	16	N. 0–1	Sea slight Swell slight	Dense fog 50 yards and less	0	14·5	—	8·0	5·30	—	—
							4	13·8	14·8	—	4·52	—	—
							6	13·9	14·5	—	4·65	—	—
							8	13·8	14·8	—	5·19	—	—
							10	13·6	14·1	—	4·61	—	—
							12	13·0	13·9	—	2·85	—	—
							14	13·1	14·0	—	2·90	—	—
							15	12·9	13·3	—	0·00	trace	Bottom phosphate 2·81 mg-atoms P/M^3.
6 (*a*)	Pelican Point breakers	1100	—	N. 0–1	Sea slight Swell slight	Dense fog 50 yards and less	0	—	—	—	5·51	—	—
6 (*b*)	Pelican Point breakers	1130	—	N. 0–1	Sea slight Swell slight	Dense fog 50 yards and less	0	—	—	—	3·40	—	—
6 (*c*)	Halfway ship and Pelican Point	1145	—	N. 0–1	Sea slight Swell slight	Dense fog 50 yards and less	0	14·6	—	—	3·23	—	—

7	Lat. 22° 53′ S..... Long. 14° 27′ E.....	19/5/50 1415	18	Calm	Sea slight Swell slight	Dense fog 50 yards and less clearing and closing	0 3 5 7 9 11 13 15 17 —	15·3 14·4 13·9 13·8 13·7 13·5 13·3 13·2 13·2 —	— 15·0 15·0 14·5 14·5 14·5 14·8 15·0 15·0 —	— 8·0 7·9 7·9 7·9 7·8 7·8 7·8 7·6 7·6	— 5·77 5·27 5·38 4·39 4·33 3·32 1·94 1·33 0·00	— — — — — — — — — trace	— — — — — — — — — —	
8	Lat. 22° 45·1′ S.... Long. 14° 29·4′ E..	20/5/50 1100	12	N. 0–1	Calm	Fog-clearing at at 1100	0 7 11	13·9 — 13·1	— 16·0 16·5	7·9 7·8 7·8	6·0 4·65 1·39	— — —	— — —	
9	Lat. 22° 45·1′ S.... Long. 14° 29·4′ E...	20/5/50 1135	16	Calm	Calm	Fog-clearing at 1100	0 7 10 15 —	15·5 14·0 13·5 13·0 —	— 15·0 15·0 15·3 —	— 7·9 7·9 7·8 7·7	— 6·29 6·39 4·42 1·25	— — — — —	— — — — —	
10	Lat. 22° 45·1′ S.... Long. 14° 26′ E.....	20/5/50 1240	43	Calm	Sea slight Swell slight	Clear fog bank to North	0 20 30 40 42	14·6 13·2 12·7 12·4 12·4	— 14·9 14·4 15·0 15·4	7·9 7·8 7·8 7·6 7·6	5·07 2·99 0·89 0·02 0·00	— — — — trace	— — — — —	
11	Lat. 22° 46·6′ S.... Long. 14° 20·6′ E..	20/5/50 1300	66	N. 0–1	Sea slight Swell slight	Clear fog bank to North	0 20 30 40 50 62 64 —	14·5 13·1 12·8 12·5 12·3 12·3 12·3 —	— 15·5 14·5 14·2 14·2 15·0 17·8 —	— 7·9 7·8 7·8 7·8 7·8 7·7 7·7	4·46 3·01 1·64 0·73 0·00 0·05 0·00 —	— — — — — — — —	— — — — — — — —	
12	Lat. 22° 48·6′ S.... Long. 14° 24·6′ E..	20/5/50 1430	58	N. 0–1	Sea slight Swell slight	Clear fog bank to North	0 20 30 40 50 57	14·7 13·1 12·8 12·6 12·4 12·2	— 15·0 15·0 13·9 14·0 14·2	7·9 — 7·7 7·7 7·7 7·6	5·04 2·81 1·64 0·55 0·03 0·00	— — — — — —	— — — — — —	
13	Lat. 22° 52·9′ S.... Long. 14° 31·6′ E....	22/3/50 1130	12	E. 4–6	Sea slight Swell slight	Clear.	0 6 11	15·9 15·5 14·5	— 20·0 22·0	8·0 8·0 7·8	6·20 6·30 2·89	— — —	— — —	
14	Lat. 22° 53′ S..... Long. 14° 30·4′ E..	22/3/50 1200	14	E	Sea slight Swell slight	Clear	0 6 13	16·8 15·3 14·1	— 19·4 18·5	7·9 — 7·8	5·84 6·55 2·89	— — —	— — —	
15	Lat. 22° 52·3′ S.... Long. 14° 26·2′ E..	22/3/50 1240	38	Calm	Sea slight Swell slight	Clear	0 10 20 30 37	15·4 13·6 13·2 12·6 12·7	17·0 15·8 16·8 17·0 —	8·0 7·8 7·8 7·8 7·7	5·40 4·28 2·90 2·02 0·00	— — — — 6·1	— — — — —	
16	Lat. 22° 52·3′ S.... Long. 14° 19·6′ E..	22/5/50 1430	77	S.W. 4–6	Sea slight Swell slight	Clear	0 10 20 30 40 50 60 70 76	14·9 13·4 12·9 12·6 12·5 12·3 12·2 12·2 12·2	— 15·0 14·5 14·3 14·1 14·1 14·0 15·0 16·0	8·0 7·9 7·8 7·8 7·7 7·7 7·7 7·6 7·6	4·80 3·61 1·76 1·26 0·52 0·40 0·04 0·02 0·00	— — — — — — — — 5·88	— — — — — — — — Phosphate bottom 76 metres, 0·32 mg-atoms P/M^3.	

B.—DOMINANT PHYTOPLANKTON, WALVIS BAY.

Station 1.

Rich Catch:
Fragilaria spp. (predominant).
Stephanopyxis turris. (Fairly large numbers.)
Chaetoceros spp.
Chaetoceros curvisetus.
Rhizosolenia spp. (Fairly large numbers.)
Coscinodiscus spp.
Coscinodiscus janischii and gigas.
Nitzschia seriata.

Station 2.

Thick Gelatinous Catch.—Fragilaria spp. by far the most predominant type–in tremendously long, ribbon-like bands
Fragilaria spp. (Predominant.)
Stephanopyxis turris. (Fair numbers.)
Rhizosolenia spp. (Present but not in abundance.)
Chaetoceros curvisetus. (Few.)
Ch. constrictus.

Station 3.

Chaetoceros socialis. (Predominant.)
Ch. curvisetus.
Ch. atlanticum.
Nitzschia seriata.
Fragilaria spp.
Coscinodiscus spp. (Few.)

Station 4.

Chaetoceros socialis. (Predominant.)
Chaetoceros curvisetus.
Chaetoceros spp.
Nitzschia seriata.
Riddulphia spp.
Asterionella spp.
Fragilaria spp.
Coscinodiscus spp. (Few.)

Station 5.

Gelatinous catch.
Fragilaria spp. (Predominant.)
Chaeteceros spp.
Rhizosolenia spp.
Stephanopyxis turris.
Stephanopyxis spp.
Asterionella spp.
Nitzschia seriata.
Chaetoceros socialis.

Station 6.

Chaetoceros curvisetus.
Chaetoceros spp.
Stephanopyxis turris.
Nitzschia seriata.
Asterionella spp.
Stephanopyxis spp.

Station 7.

Stephanopyxis turris.
Stephanopyxis spp.
Chaetoceros curvisetus.
Rhizosolenia spp. (In far greater quantities than in any sample hitherto examined.)
Asterionella spp.
Fragilaria spp.
Chaetoceros socialis.
Peridinium divergens.
Peridinium spp.
Coscinodis spp. (Small numbers.)
Nitzschia seriata.
Larvae. (In considerable numbers.)

Station 8.

Fragilaria spp.
Chaetoceros curvisetus.
Chaetoceros spp.
Stephanopyxis spp.
Rhizosolenia spp.
Nitzschia seriata.
Coscinodiscus spp. (Few.)

Station 9.

Dense and cloudy in upper layer when settled.
Chaetoceros socialis and other spp. (Predominant.)
Rhizosolenia.
Nitzschia seriata.
Chaetoceros curvisetus.
Stephanopyxis turris.
Asterionella spp. (Few.)
Fragilaria spp. (Few.)

Station 10.

Not very dense.
Chaetoceros socialis.
Chaetoceros curvisetus.
Asterionella spp. (In quantity.)
Thalassiosira spp. (In considerable quantity.)
Coscinodiscus spp.
Stephanopyxis turris.
Nitzschia seriata.
Peridinium divergens. (Few.)

Station 11.

Sparse.
Chaetoceros socialis. (Predominant.)
Asterionella spp. (In quantity.)
Chaetoceros curvisetus.
Thalassiosira spp.
Nitzschia seriata.
Coscinodiscus spp. (Few.)
Rhizosolenia spp. (Very few.)

Station 12.

Chaetoceros socialis. (Predominant.)
Chaetoceros spp.
Asterionella spp.
Fragilaria spp.
Coscinodiscus spp. (Few.)
Thalassiosira spp.
Chaetoceros socialis.
Chaetoceros altanticus.
Nitzschia seriata.
Peridinium divergens. (Few.)

Station 15.

Chaetoceros socialis.
Chaetoceros curvisetus.
Asterionella spp.
Rhizosolenia spp. (Very large quantity.)
Nitzschia seriata.
Fragilaria spp.
Stephanopyxis turris.
Larvae.
Crustacea. (Numerous copepods.)

Station 16.

Chaetoceros socialis.
Chaetoceros curvisetus.
Asterionella spp.
Coscinodiscus spp. (Few.)
Thalassiosira spp.
Chaetoceros spp.

"A".—23/5/50, 8 p.m. off Pelican Point.

Fragilaria spp.
Rhizosolenia spp.
Asterionella spp.
Chaetoceros socialis.
Peridinium divergens.
Stephanopyxis turris.
Coscinodiscus spp.
Thalassiosira spp.
Chaetoceros curvisetus.
Chaetoceros spp.
Few larvae.

"B".—23/5/50. Halfway between Walvis Bay and Swakopmund.

Denser catch than above.
Fragilaria spp.
Rhizosolenia spp.
Peridinium divergens.
Peridinium spp.
Stephanopyxis turris.
Thalassiosira spp.
Asterionella spp.
Chaetoceros socialis.
Chaetoceros spp.
Nitzschia seriata.
Few larvae.
Tintinnus spp.

Diatoms Identified in Green Mud from Anchorage (1934).

Coscinodiscus marginatus.
Coscinodiscus radiatus.
Coscinodiscus asteromphalus.
Coscinodiscus janischii.
Melosira sulcata.
Asteromphalus humboldtii.
Asteromphalus heptactis.
Entopyla australis.
Pleurosigma decorum.
Pleurosigma regidum.
Biddulphia longicruris.
Auliscus sculptus. . .
Aclinoptchus crassus.
Triceratium alternans.
Triceratium punctatum.
Triceratium brookei.
Dicladia capreolus.
Cerataulus turgidus.
Navicula lyra.
Actinocyclus crassus.
Nitzschia sigmoidea.
Campylodiscus spp.
Chaetoceros spp.

C.—ST. HELENA BAY PHYTOPLANKTON.

Dominant Species in Surface Samples,

Date: 23/5/50; Station OO.
Lat. 32° 40′ South.
Long. 18° 00′ East.
(Catch sparse.)
Coscinodiscus radiatus.
(Preponderance.)
Peridinium divergens.
Chaetoceros spp.
Larvae.

Date: 23/5/50; Station NN.
Lat. 32° 35′ South.
Long. 18° O′ East.
(Catch sparse.)
Coscinodiscus radiatus
(Preponderance.)
Peridinium divergens.
Chaetoceros spp.
Globigerina spp.
Larvae.

Date: 28/5/50; Station OO.
(Catch sparse.)
Coscinodiscus (large).
(In preponderance.)
Peridinium divergens.
Ceratium tripos.
Chaetoceros spp.
Globigerina spp.

Date: 28/5/50; Station NN.
(Catch sparse.)
Coscinodiscus spp.

Peridinium divergens.
Chaetoceros spp.
Larvae.

APPENDIX III.

STATION LIST—R.R.S. "WILLIAM SCORESBY".

Station.	Position.	Sound, Metres.	Date.	Depth.	Temperatures. °C.	O_2 ml. l.	P mg-atoms/m^3.	Remarks.
976	Lat. 22°50′ S....	3100	6/3/50	0	19·3	5·37	0·58	About 160 miles offshore.
	Long. 11° 38′ E..	—	—	50	19·2	5·26	0·58	—
				75	14·2	—	0·92	—
				100	13·4	4·18	1·08	—
				500	6·3	3·12	2·36	—
				900	4·0	3·19	2·36	—
				1,450	3·3	4·38	1·85	—
				3,098	2·5	—	2·75	In yellow mud (filtered).
977	Lat. 22° 39′ S...	1600	6/3/50	0	18.4	5·30	0·50	About 125 miles offshore.
	Long. 12° 16′ E.	—	—	20	18·4	15·37	0·50	—
				30	15·9	—	1·08	—
				50	14·1	13·78	1·08	—
				100	12·6	3·39	1·25	—
				300	9·2	0·92	2·23	—
				600	5·9	2·38	2·23	—
				820	4·4	13.12	2·23	—
				1,490	3·4	4·07	1·85	—

APPENDIX III (continued).

Station.	Position.	Sound. Metres.	Date.	Depth.	Tempera-tures.	0_2 ml/l.	P mg-atoms/m^3.	Remarks.
978	Lat. 22° 28′ S...	932	7/3/50	0	18·2	5·16	0·75	About 100 miles offshore.
	Long. 12° 42′ E.			20	17·9	3·17	0·88	—
				30	14·8	—	1·76	—
				50	14·3	5·09	1·76	—
				100	13·1	2·19	1·98	—
				400	7·9	1·46	2·10	—
				600	5·7	2·31	2·75	—
				820	4·2	3·21	2·81	—
979	Lat. 22° 47′ S...	139	7/3/50	0	16·7	8·07	0·20	About 52 miles offshore.
	Long. 13° 35′ E..			20	15·3	4·78	0·33	—
				30	13·7	—	1·68	—
				50	13·1	2·21	0·92	—
				100	12·4	1·19	1·85	—
980	Lat. 22° 44′ S...	106	8/3/50	0	17·0	6·43	0·25	—
	Long. 14° 08′ E..			10	15·4	—	2·49	—
				20	14·3	2·56	2·75	—
				30	13·3	—	2·49	—
				50	13·1	0·13	3·01	—
				100	12·7	0·37	2·61	About 28 miles offshore.
981	Lat. 22° 44′ S...	64	8/3/50	0	16·7	0·33	1·42	About 10 miles offshore.
	Long. 14° 20′ E..			10	14·9	—	1·68	—
				20	13·5	0·87	2·10	—
				50	13·3	0·11	2·95	—
988	Lat. 25° 12′ S...	135	11/3/50	0	16·3	7·89	1·08	Near Easter Cliffs.
	Long. 14° 22′ E..			20	13·8	3·61	3·50	About 25 miles offshore.
				50	12·3	1·48	1·42	—
				100	11·9	0·34	2·49	—
				125	11·8	0·25	2·88	—
989	Lat. 25° 11′ S...	70	11/3/50	0	14·8	7·06	1·42	Near Easter Cliffs.
	Long 14° 39′ E..			20	13·1	2·05	1·98	About 10 miles offshore.
				50	12·7	0·22	2·95	—
				60	12·6	0·29	2·92	—
990	Lat. 25° 35′ S...	143	11/3/50	0	14·8	—	—	Green black mud.
	Long. 14° 27′ E.			131	11·5	—	—	(Stinking mud—H_2S.).

SECTION IX.

PLATES I–IX.

EXPLANATION.

PLATE I.—Bottom contours along the West Coast from Cape Point to the Kunene River.
PLATE II.—The Benguela Current—the hatched area off Walvis Bay indicates the Azoic Zone.
PLATE III.—*Fig.* 1.—Dead fish at Walvis Bay, December, 1929.
Fig. 2.—The disposal of dead fish at Walvis Bay, December, 1929.
PLATE IV.—Mud Island in Walvis Bay; as seen from Pelican Point, June 2, 1900.
PLATE V.—Chart showing the positions of the stations worked by the Patrol Vessel " Namib ".
PLATE VI.—Electron micrograph (x 15,000) of the halophytic sulphate-reducing bacterium (*Desulphovibrio desulphuricans*).
PLATE VII.—Diagrammatic representation in section of the surface temperature and oxygen content off Walvis Bay during normal and mortality times.
PLATE VIII.—Sectional diagram showing the temperature and oxygen content conditions at Latitude 22° 44′ South on 7th/8th March, 1950.
PLATE IX.—Chart showing the Walvis Ridge connecting with the Atlantic Ridge. (After Schott.)

PLATE 1.

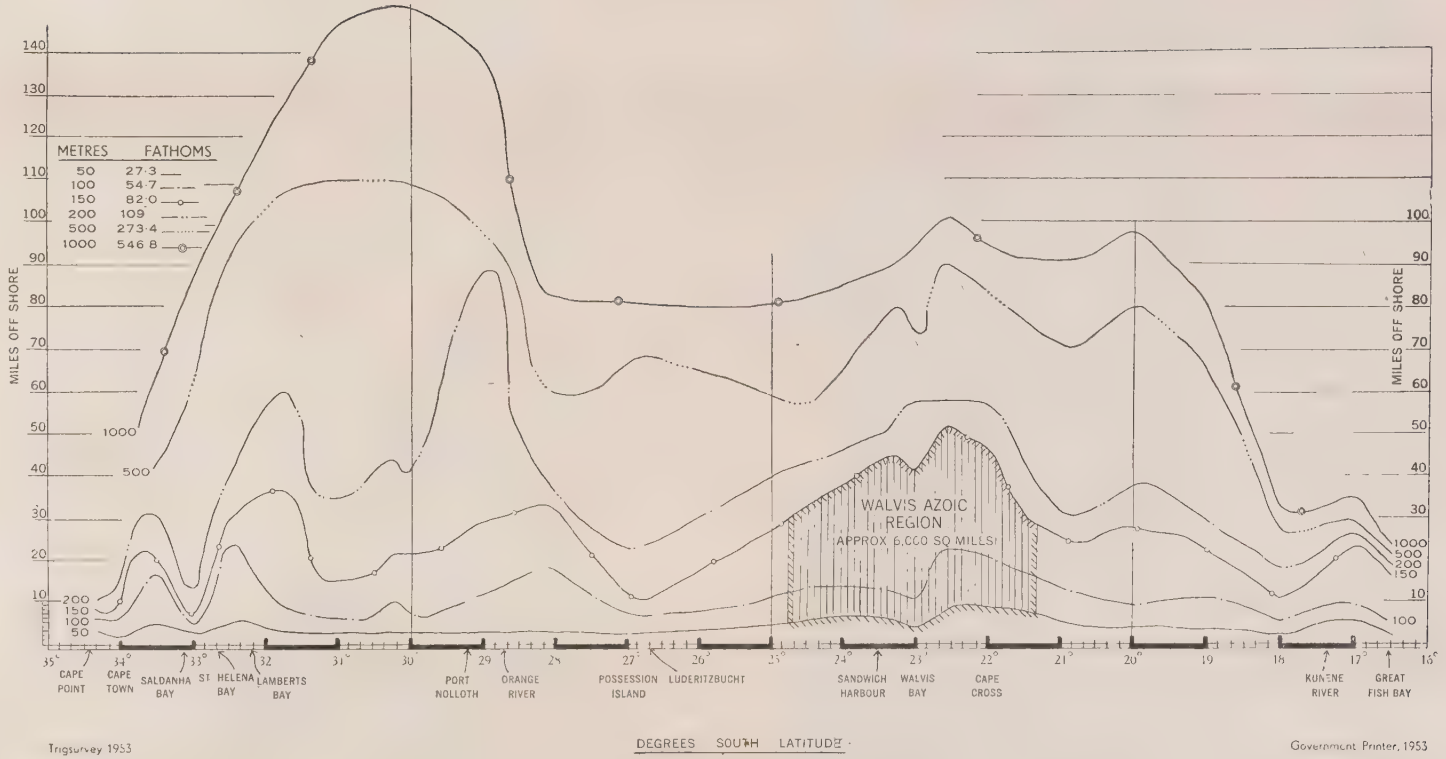

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PLATE II.

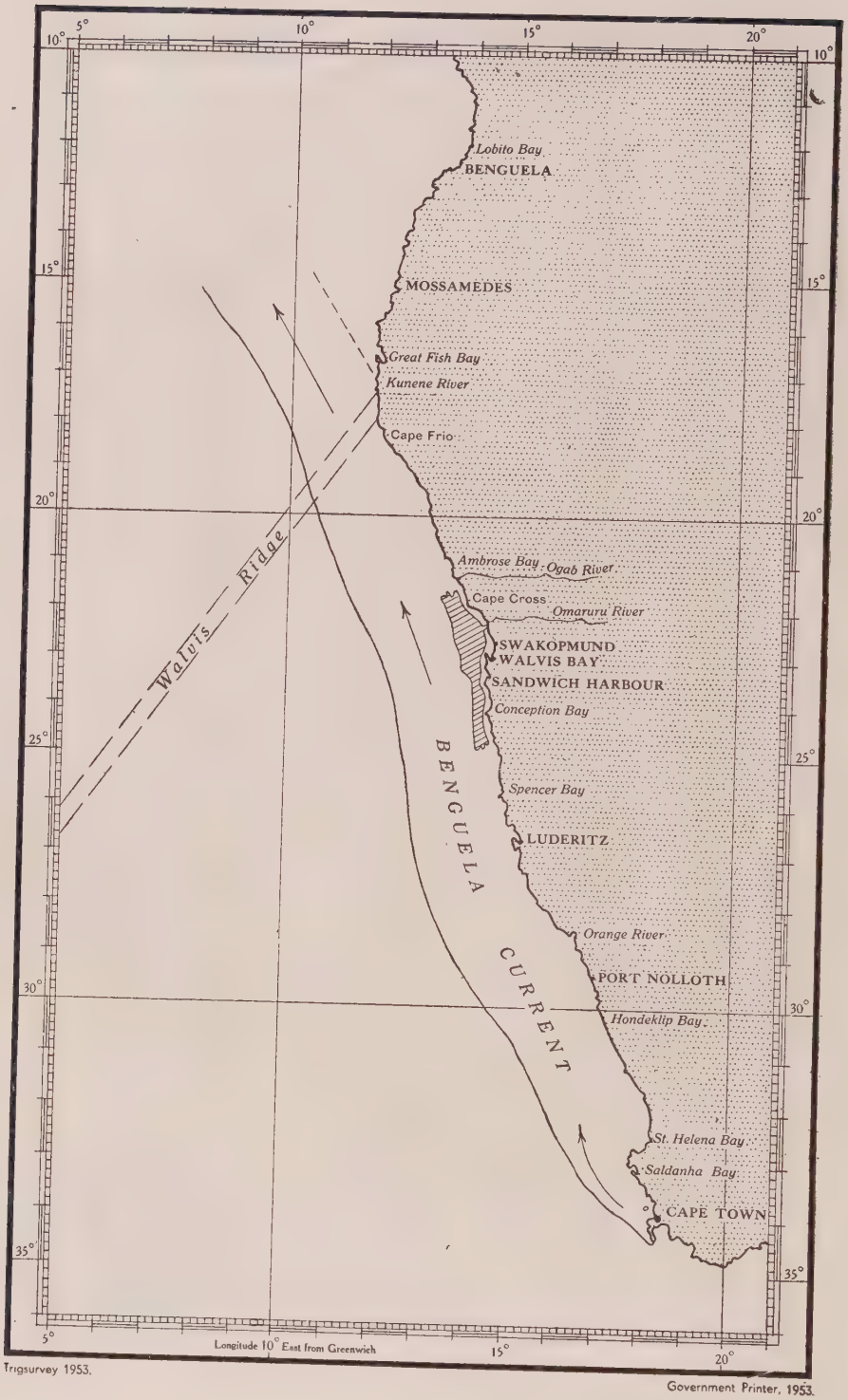

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PHOTO: H. Offen, Swakopmund.

PHOTO: H. Offen, Swakopmund.

PLATE IV.

PHOTO: F. W. Waldron—Reproduced by Courtesy of the Royal Society of South Africa.

PLATE V.

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PLATE VI.

PHOTO: K. R. Butlin, Microbiological Section, United Kingdom, Department of Scientific and Industrial Research.
(*Magnification* × 15,000).

PLATE VII.

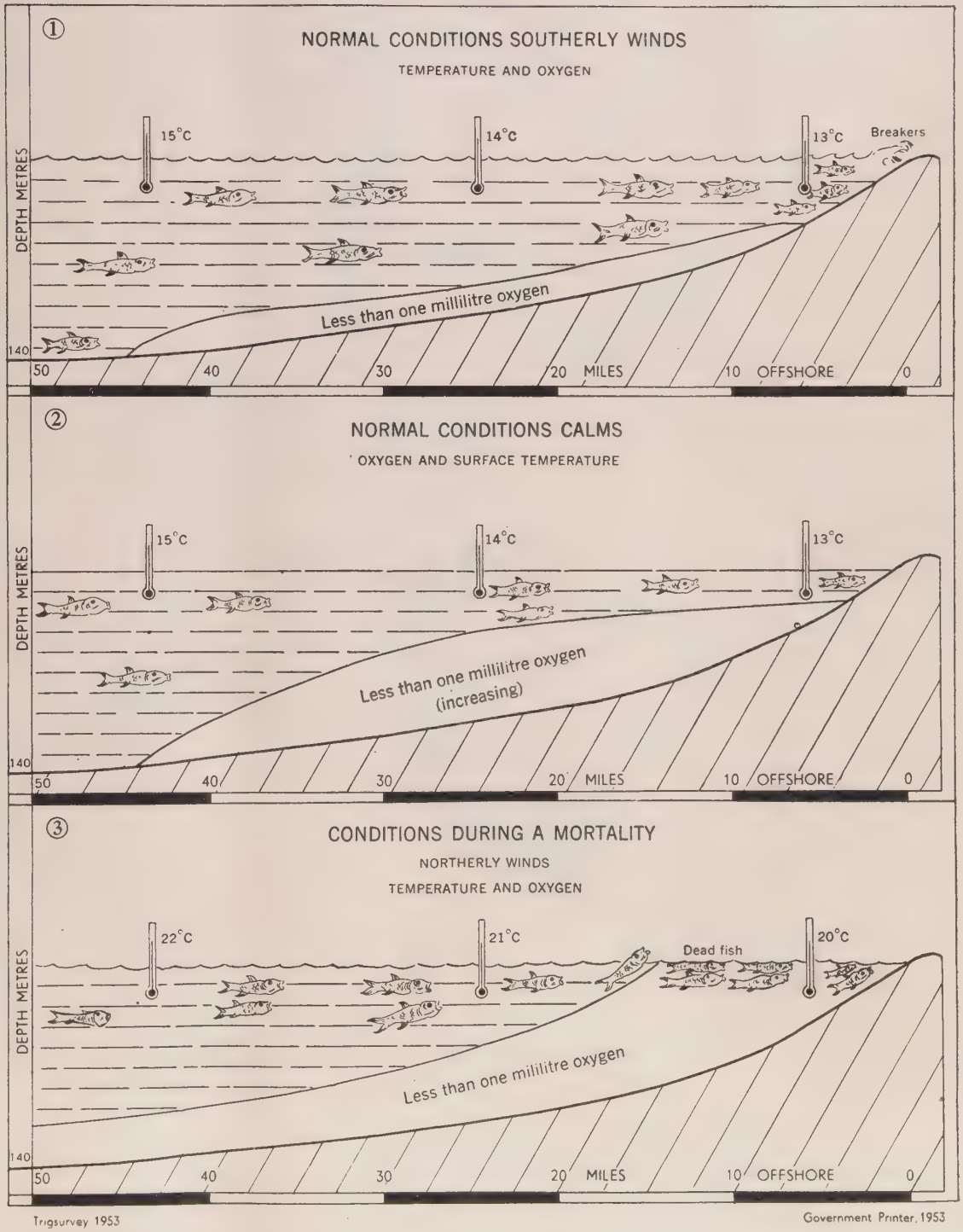

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PLATE VIII.

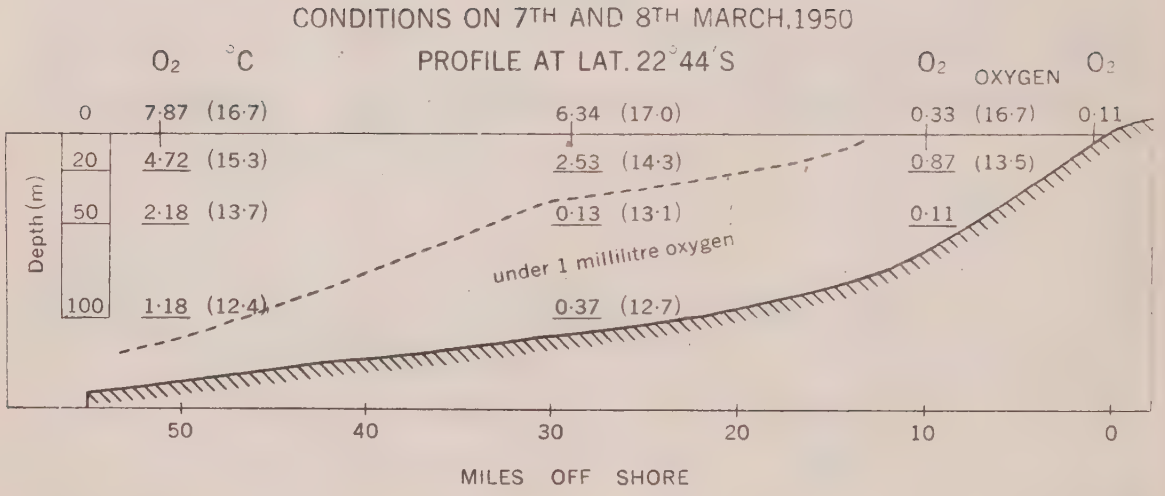

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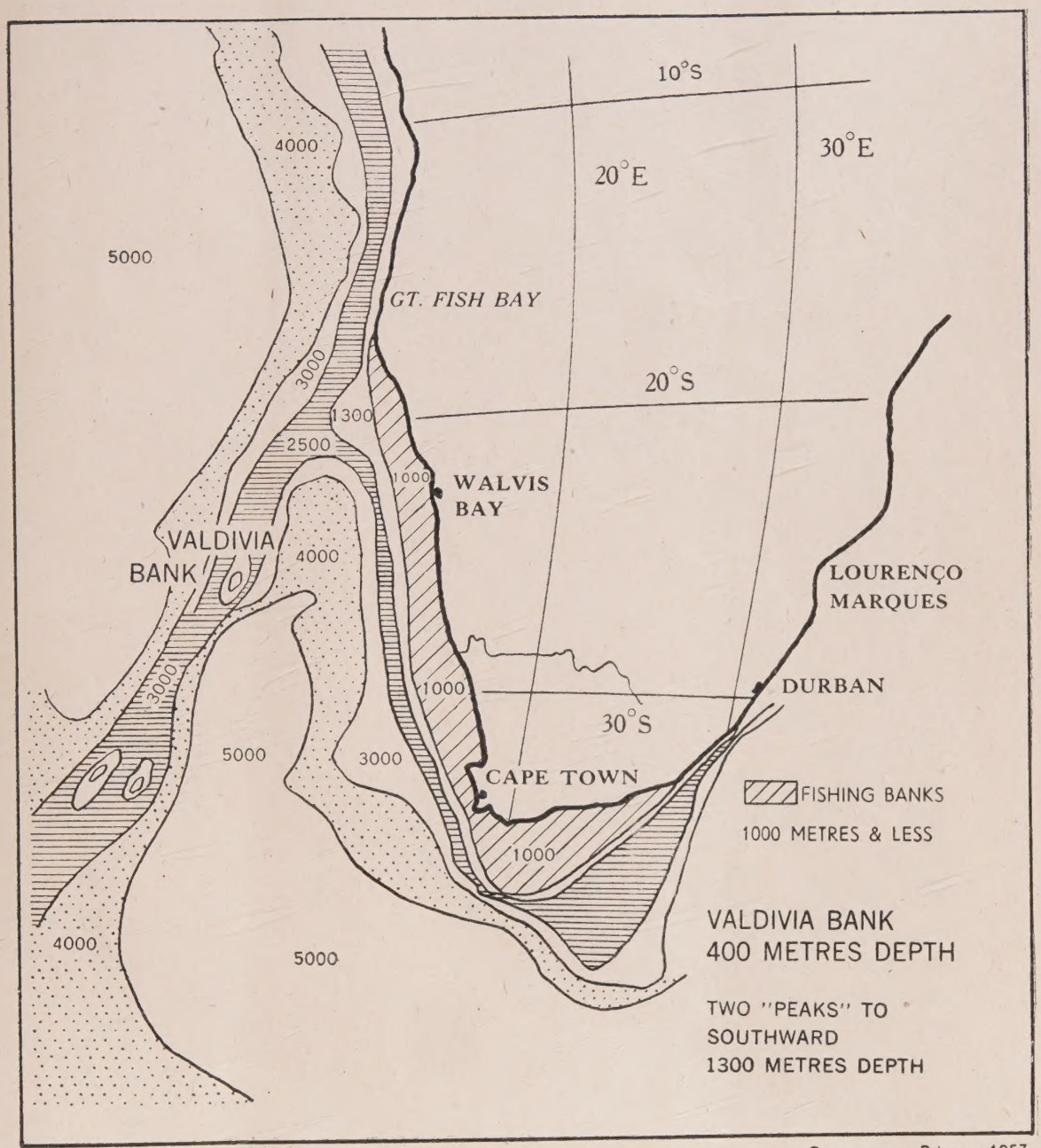
PLATE IX.



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